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PROJECT FOGGY CLOUD IV. PHASE II. WARM FOG MODIFICATION BY ELECTROSTATICALLY CHARGED PARTICLES

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Naval Weapons Center
China Lake, California

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Project Foggy Cloud IV

Phase II. Warm Fog Modification by Electrostatically Charged Particles

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ABSTRACT

Foggy Cloud IV, Phase II, is part of a continuing series of experiments concerning the modification and dispersal of warm fog. The primary purpose of Phase II was to evaluate the use of electrostatically charged particles as a means of improving visibility in warm fog. A charged-drop-producing system comprising an induction charging system and a water delivery system was developed for charging and delivering water drops. Tests were conducted at the Arcata-Eureka airport, McKinleyville, Calif., from 14 September to 5 November 1971, using a manned hot-air balloon as a research platform.

Although a practical charging and delivery technique was developed, testing was inconclusive because of the lack of fog and the encountering of an unanticipated phenomenon, termed "ground effect."

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FOREWORD

Project Foggy Cloud is a continuing research and development program conducted by the Earth and Planetary Sciences Division of the Research Department, Naval Weapons Center, for AIR-05F, Naval Air Systems Command.

Phase II of Foggy Cloud IV, the fourth in a series of warm fog modification experiments, began 14 September and ended 5 November 1971. Nineteen tests were performed. A primary objective for this series was the evaluation of electrostatically charged particles as a means of improving visibility in warm fog. From the results reported herein, a choice can be made of promising leads for future work.

This report is released at the working level. It has been reviewed for technical accuracy by R. J. Stirton. Because of the continuing nature of the warm fog research program, tentative conclusions presented here are subject to later review and change.

Because testing was performed by NWC in collaboration with the U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, an activity of the Army Electronics Command, this report is issued with the technical report numbers of both NWC (TP 5338) and ASL (ECOM 5426).

Released by
PIERRE ST.-AMAND, *Head*
Earth and Planetary Sciences Division
20 June 1972

Under authority of
HUGH W. HUNTER, *Head*
Research Department

CONTENTS

SUMMARY

From 14 September to 5 November 1971 the Naval Weapons Center, working in collaboration with the U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, conducted the field tests of Phase II of Project Foggy Cloud IV. Laboratory work, which preceded the field tests, was conducted at China Lake, Calif., and the field tests were performed at the Arcata-Eureka airport in northern California, where several such projects have been conducted in the past.

The primary purpose of Phase II was to develop a field system for charging and delivering water drops from a manned hot-air balloon to ascertain the effect of the charged drops on dispersing warm fog. A previously unobserved phenomenon, which was termed "ground effect," interfered with the field tests, and studies were conducted to determine the origin and magnitude of this ground effect.

Because of the unavailability of warm fog during the field test period, the tests to determine the effect of charged particles on fog were not completed. However, a practical charged-drop-producing system was developed for future use. The system helped to significantly reduce the number of finer particles ($<10 \times 10^{-6}$ meter radius) with respect to the median spray drop of 50×10^{-6} meter radius, thus eliminating possible fog enhancement by these fine particles.

INTRODUCTION

The Foggy Cloud warm fog dispersal projects were initiated in 1968 in response to a requirement for military aircraft operations under conditions of reduced visibility (Ref 1). The Arcata-Eureka airport, McKinleyville, Calif. (Ref. 2), was selected as a test site for the Foggy Cloud projects because of its high incidence of fogs; relatively low volume of air traffic; excellent facilities, including instrumentation; and wealth of information on the occurrence and characteristics of fog.

Project Foggy Cloud I (Ref. 1), conducted in 1968, was a screening project, in which warm fog dispersal techniques, equipment, and seeding agents were screened. Project Foggy Cloud II, conducted in 1969, was in part a continuation of Project Foggy Cloud I and in part an effort to improve Foggy Cloud I delivery techniques. Project Foggy Cloud III (Ref. 2), conducted in 1970, saw substantial technique improvement, both in targeting and delivery. Maximum effectiveness of large helicopters under the Arcata fog conditions was established.

Project Foggy Cloud IV utilized knowledge gained from previous projects to enhance existing techniques. It was conducted in two phases. The two phases were distinguished primarily by the type of delivery system and vehicle. Phase I utilized fixed-wing aircraft for testing, and the seeding agent had little or no electrostatic charge. Phase I will be the subject of a separate report.

Phase II, the subject of this report, placed major emphasis on developing and field-testing a system for charging and delivering charged water drops into warm fog from a manned hot-air balloon to ascertain the effect of the charged drops on dispersing the fog. Laboratory investigations were performed at the Naval Weapons Center and included preliminary tests and the selection, design, and fabrication of the

charging system. Field experiments were conducted at Arcata in collaboration with the U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, from 14 September to 5 November 1971. A manned hot-air balloon was used as the lifting mechanism for the entire charged-drop-producing system, which consisted of the water delivery system and the induction charging system. The water delivery system was made up of a spray assembly, which included nozzles and plumbing, and a water tank and a pressure tank. The charging system consisted of induction rings, a battery, insulators, and wiring.

Throughout this report both English and metric units appear. Popular usage determined which units are used in each case. For instance, gal/hr is used rather than l/hr, and psi rather than N/m^2. Because it is likely that an induction charging system would be constructed in a machine shop using English tools and measurements, such dimensions are given in inches, feet, etc. In cases where metric units such as cubic centimeters (rather than cubic inches) and 10^{-6} meters (rather than milliinches) are in more popular usage, the metric units are used.

BACKGROUND

Considerable evidence exists to suggest that electric forces may have profound effect upon the growth of water drops in warm clouds and fogs by collision and coalescence. Cochet (Ref. 3) showed theoretically that highly charged drops of less than about a 60 X 10^{-6} meter radius would possess very much larger collection efficiencies than similar but uncharged drops. Moore and Vonnegut (Ref. 4) observed the growth of precipitation in thunderclouds with very sensitive radar equipment. They estimated that, for the precipitation to grow at the recorded rate, the values of the drop collection efficiencies must have been 4 to 10 times greater than the accepted values pertaining to nonelectrified clouds. In order to explain the observed gushes of rain or hail that frequently follow lightning flashes in thunderstorms within short time intervals, Vonnegut and Moore (Ref. 4) put forward the theory that a lightning discharge introduces a large charge into the cloud opposite in polarity to the drops in that region. These ions heavily charge the nearby drops, and these drops are forced outward at very high velocities by forces of mutual repulsion. Coalescence with several other oppositely, and lesser, charged drops follows, leading to drops large enough to precipitate out of the cloud and continue to grow thereafter by coalescence as they fall.

Clearly the influence of electric forces is a maximum for very small drops, and the use of such small particles would result in the greatest economy of seeding material. However, the fall velocities of these very small drops are very low, and larger drops must be utilized in practical fog modification experiments to provide realistic fog dispersal times. The optimum drop size is probably such that any reduction in the electrical effect due to drop growth is offset by a compensating increase in the purely hydrodynamic collection efficiency. Drops in the size range 20 X 10^{-6} to 60 X 10^{-6} meter radius probably represent the optimum for the purposes of the fog modification procedures presently envisaged.

The successful introduction of large quantities of highly charged drops into confined regions of a fog will result in the generation of substantial electric fields, which may modify the interactions of natural fog drops over regions of the fog beyond the immediate influence of the charged material. The general consensus (Ref. 3 and 4) seems to indicate that electric fields greater than 20 kV/m will be required to influence significantly the stability of a natural fog and, while there may be considerable difficulty in engineering these large electric fields, the potential rewards are high enough to warrant further investigation.

LABORATORY INVESTIGATIONS

CHARGING SYSTEMS

Three basic systems for charging water drops were considered: (1) the contact system, (2) the corona system, and (3) the induction system.

Contact System

In a contact system the entire spray assembly is charged with 50,000 to 100,000 volts, thereby forming an electric field between the spray assembly and "grounded environment" to charge water drops. The contact system was given a low priority for use in field tests because of the potential hazards involved in the use of such high voltages in a foggy environment.

Corona System

The corona system is effective in producing highly charged drops by supplying an abundance of ions in the vicinity of the spray but requires high electromotive forces (emf). This system was discarded primarily because of the great weight, volume, expense, and time involved in developing a 100,000-volt power supply to operate in damp environments. However, the corona system was not excluded from future consideration since it potentially offers a higher charge-to-surface-area ratio than the contact or induction system.

Induction System

The induction system, which was selected for the Phase II field tests, requires application of an emf between the induction rings and the spray assembly nozzles; the induction rings are placed around and insulated from the nozzles. This system has the advantage of requiring only 1,000 to 5,000 volts to produce usable fields that yield charge-to-surface-area ratios as high as the contact system, which requires 50,000 to 100,000 volts. When the induction system is connected with a nozzle grounded, it requires no current from the emf source, hence no power. Figure 1 shows four connection options. All of these connections are equally effective in producing high charge-to-surface-area ratios. The low emf requirements make the induction system

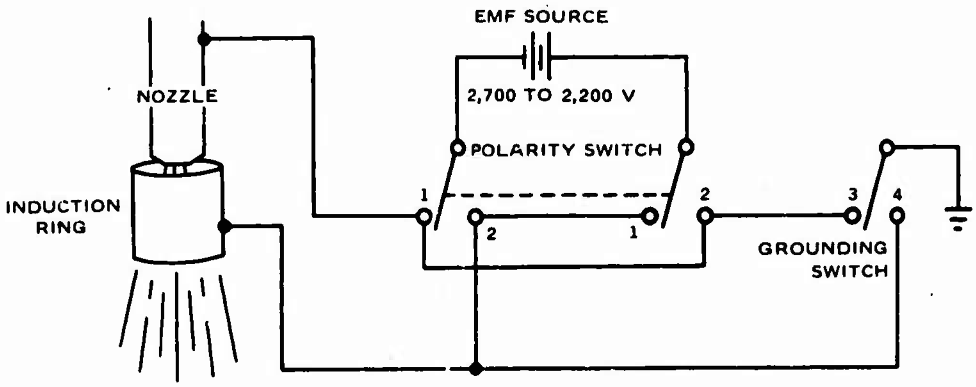


FIG. 1. Induction System Connection Options. With polarity switch in position 1, ring is negative with respect to nozzle and ejected drops are positive; with polarity switch in position 2, ring is positive with respect to nozzle and ejected drops are negative; with grounding switch in position 3, nozzle is grounded and no current is required of battery; with grounding switch in position 4, ring is grounded and nozzle current is required of battery.

compatible with moist environments, and the zero power requirement makes possible an emf source consisting of radio-type B batteries connected in series. Details of the induction system operation are given below.

A nozzle acts as an electron sink or source for the drops, depending upon whether the ejected drops are positive or negative, respectively. All electrons leaving the drops (for positive drops) or entering the drops (for negative drops) must do so via the nozzle. The induction ring is insulated and, with the nozzle grounded, no current exists in the induction ring circuit. If the ring is grounded, then the only path between the nozzle and ground is through the emf source, and the emf source will therefore be required to provide the charging current. The direction of current through the emf source will be such as to require it to be an energy source. Figure 2 illustrates the current paths and directions for the various connection options.

A charged drop in space represents a higher energy level than the same drop uncharged. However, the emf source does not necessarily supply the higher energy. In Fig. 2a and c the emf source does not supply energy; it provides only a field for initial drop charging. The energy is supplied mechanically in a manner similar to the way a Van de Graaff generator operates, i.e., by forcing an initially charged particle in a direction opposed to the force on the particle. The energy source in the drop-by-drop mode is the operator who lifted the water into the container for the drops to fall out of; the energy source in the spray mode is the pressure tank.

In Fig. 2b and d the emf source does supply some of the energy. It is noted that the nozzle and drop polarity are the same, reducing or eliminating attractive forces between the drop and nozzle but not eliminating attractive forces between the drop and the now grounded induction ring. In Fig. 2b and d, then, some of the higher

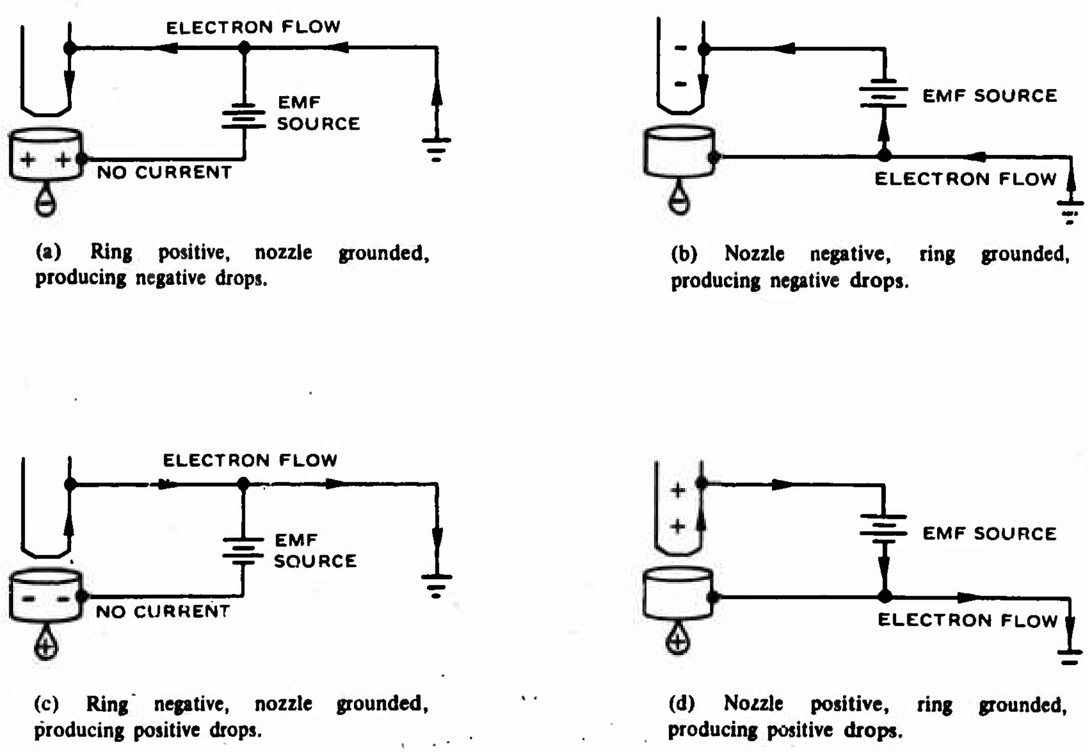
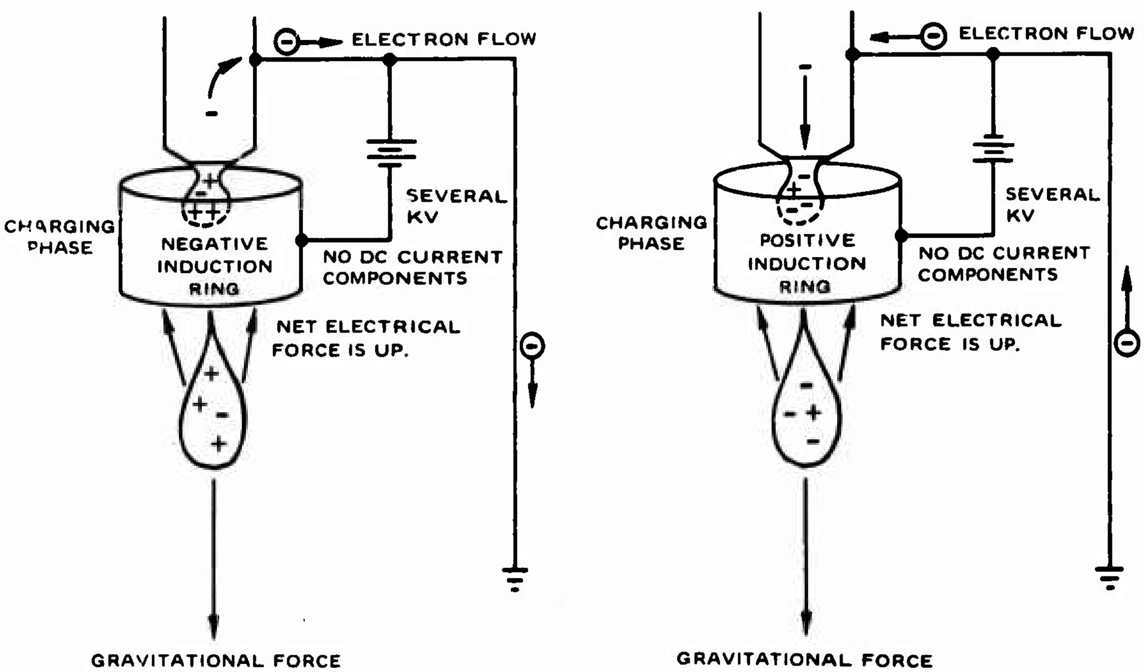


FIG. 2. Induction System Connection Option Current Paths.

energy of a charged drop in the field free region is provided by the emf source and some by mechanical energy sources.

Charging of the drop occurs because like charges repel, or specifically stated, electrons that have mobility in the drop repel each other and are attracted to areas of relative electron deficiency. Actually even in materials that are considered good insulators, such as oil, electrons have sufficient mobility to permit charging if sufficient time is allowed. An apparatus that obtained charge-to-surface-area ratios on oil drops, nearly as high as those obtained with water, will be described under the Induction Charging System Design section of this report.

Figure 3 illustrates a single-drop-at-a-time charging sequence in which gravity is the dominant factor in removing the drop from the electric field region. When a spray is used, the dominant factor in removing the drop from the electric field region is the kinetic energy in the drop provided by the water delivery system's pressure source. In both cases the process of inducing charge is the same; only the mechanical method of providing the energy required to remove the charged drop from the electric field region is changed. In Fig. 3a charging occurs because the drop is in electrical contact with the nozzle. Therefore the electrons can easily leave or enter the drop and will leave it because the induction ring, being negatively charged, repels them. Under gravity's pull, the drop breaks away from the nozzle, but as it is still in the region of high electric field it loses none of its charge when it is separated from the nozzle. After separation from the nozzle, and under the force of gravity, the drop is removed from the high electric field region. However, the drop retains its charge because it is not in contact with an electron source or sink. In Fig. 3b the charging sequence is identical to that in Fig. 3a, except that the electrons enter the drop because the induction ring, being positive, attracts them, with the net result that the drop leaves with a negative charge.



(a) Positive current.

(b) Negative Current.

FIG. 3. Gravity-Assisted Single-Drop-at-a-Time Charging Sequence.

In both Fig. 3a and 3b the drops are no longer in electrical contact with the nozzle, and hence cannot gain or lose electrons;[1] the net electrical force is up; and the energy of the drops is increasing by virtue of their downward motion. In its formative stages, the drop is gaining or losing electrons, incipiently altering the field between the ring and the drop, causing a minute, short duration charging current in the ring circuit. This represents a minute energy output from the emf source. However, when the drop breaks away and leaves the high electric field region, the field is incipiently altered in an opposite direction, resulting in a minute, short duration "uncharging" current in the opposite direction that returns the energy extracted from the emf source. On this basis, there is no net energy output from the emf source. In practice, small losses due to radiation and wiring resistance would subtract from the energy returned to the emf source, resulting in a slightly smaller amount being returned than was extracted from it. Of greater significance is the occasional arcing between ring and nozzle, which represents a relatively large amount of energy extracted from the emf source, none of which is replaced. In practice, the effects of arcing were alleviated by the use of a high resistance in series with each nozzle.

Preliminary laboratory experiments were designed to verify general principles and were not limited to any practical charging system. Systems other than nozzle sprayers were investigated. Most promising of the nonnozzle charged drop producers was a parallel plate device that used the upper plate as an induction surface and the lower plate as an electron source/sink. The plates were placed as close to each other as high voltage considerations permitted. Various substances, including alcohol, engine oil, an ammonium nitrate/urea solution, chloroform, and water, were tested for chargeability, and similar charge-to-surface-area ratios were obtained for all of these materials. The induction charging arrangements used, and the actual charge-to-surface-area ratio obtained, will be given in the Laboratory Investigation Results section.

MEASURING TECHNIQUES

This section explains the methods, procedures, and techniques by which the laboratory data presented in this report were obtained.

A Faraday pail-type collector was used to measure drop charge. A collector can be any conducting surface culminating in a mostly enclosed volume ensuring a total discharge of the drop. A coffee can, open at one end and deep with respect to its diameter, is a combination collection surface and adequate Faraday pail. A radar parabola with a hole in the center resting on top of a metal container is another combination where the parabola acts as the collector and the container as the Faraday pail. Both of these arrangements were used in the laboratory. The essential features are that the collector/Faraday pail combination be insulated from ground and tied to an electrostatic emf meter or some other extremely high input impedance emf measuring instrument.

An understanding of the required impedance of the collector/Faraday pail/meter can be obtained by noting that the use of an electrostatic emf meter requires one to deal with emf's of about 4,000 to 5,000 volts before relatively accurate readings can be obtained. Using drops that measure $2{,}900 \times 10^{-6}$ meter in radius and have a charge of 62×10^{8} electrons each, and assuming a reasonable rate of 1 drop/sec, the current intercepted by the collector/Faraday pail is 62×10^{8} electrons/sec, which would yield approximately 9.9×10^{-10} ampere. Setting an arbitrary accuracy requirement of one part in 10 requires that leakage be kept to one-tenth of the drops' supplied current. It is apparent that slower drop rates will decrease accuracy with fixed

[1] Actually a free drop, i.e., one not in contact with an electron sink or source such as the nozzle, cannot gain or lose electrons as easily as when it was in contact with the nozzle. This explains why it does not immediately discharge upon leaving the electric field region. In practice, some electron leakage between the drop and the air surrounding it occurs.

leakage rates because of the lower drops' supplied current. With the above conditions, leakage current must be limited to 9.9×10^{-11} ampere. Dividing an emf of 5,000 volts by a current of 9.9×10^{-11} ampere yields 5×10^{13} ohms. This is difficult to obtain even with a dry climate. Figure 4 schematically shows this method of measuring charge per drop. The method works well for large drops ($1,500 \times 10^{-6}$ meter or more in radius) that are not deflected sufficiently by the field so as to miss the collector entirely. If a spray that produces relatively fine drops is used, the drops will be deflected by the field and miss the collector. When spray is produced the carried current is usually on the order of several microamperes, which is measurable by a sensitive ammeter. The ammeter may be substituted for the electrostatic emf meter, with the net result that the collector is grounded through the ammeter. This configuation (Fig. 4) does not allow a buildup in emf, thereby controlling the electric field and ensuring collection of the sprayed drop.

The capacitance of the collector/Faraday pail must be known to use it to measure charge per drop. This is easily found by comparing it with a known capacitance; a simple method is shown in Fig. 5. To determine charge per drop it is only necessary to count the drops, measure emf on the collector, and multiply the change in collector emf per drop by the capacitance of the collector/Faraday pail.

An alternate method of measuring spray current is to use a ground current meter, so called because of its location in the line connecting the water delivery system to ground. This requires careful insulation of the water delivery system from ground, with the exception of the path provided by the current meter. Under field conditions there is a current feedback to the spray assembly. This feedback current causes a certain effect, termed "ground effect," which is a function of distance from ground to the spray assembly. The ground-current meter measures spray current less feedback current. This feedback current is undesirable in that it subtracts from the net output of charge. During field testing, ground effect was detected by use of the ground-current meter. The use of a grounded collector system (Fig. 4) tends to

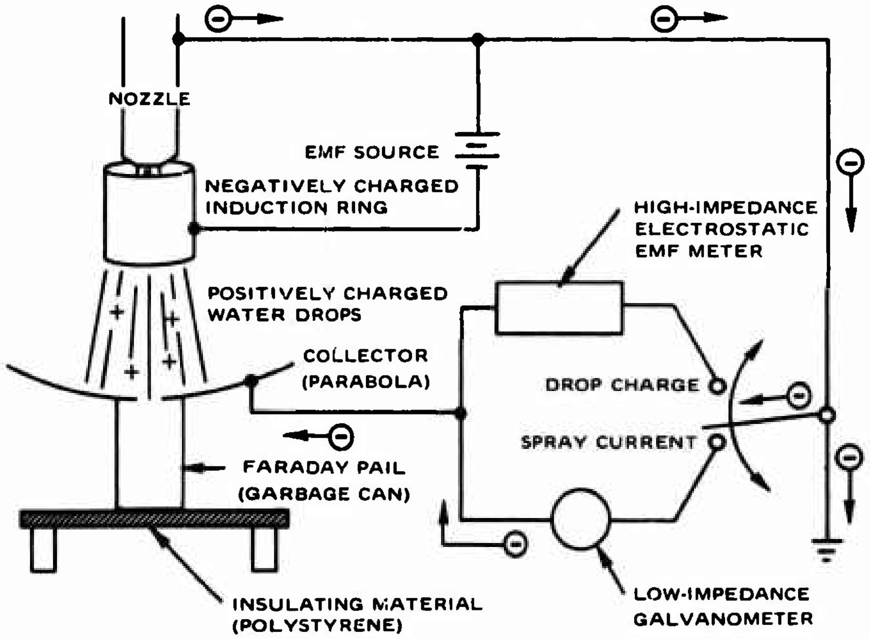
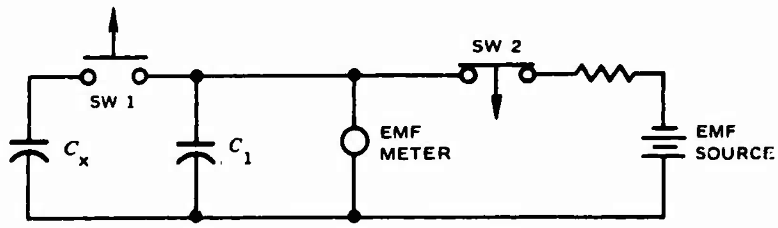
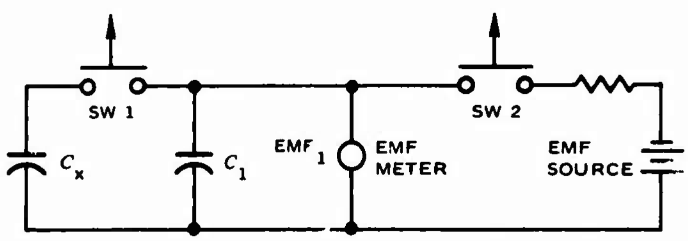


FIG. 4. Spray Current and Charge per Drop Measurement Schematic.

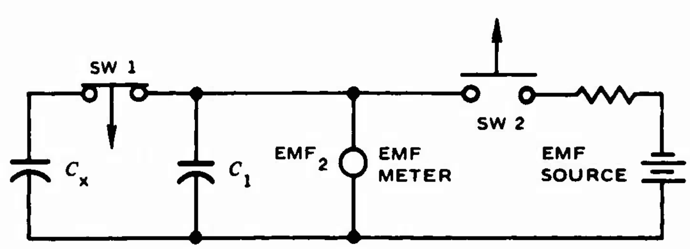


(a) Charging of C_1.



$Q = C_1 \cdot EMF_1$

(b) Opening of charging circuit and observing emf_1.



$Q = (C_1 + C_x)\, EMF_2$

$Q = C_1 \cdot EMF_1$

Q IS CONSERVED

$\therefore (C_1 + C_x)\, EMF_2 = C_1 \cdot EMF_1$

$$C_x = \frac{C_1 \cdot EMF_1}{EMF_2} - C_1$$

WHERE

C_1 IS A KNOWN CAPACITANCE

C_x IS THE UNKNOWN COLLECTOR-FARADAY PAIL SYSTEM CAPACITANCE

(c) Paralleling C_x with C_1 and observing emf_2.

FIG. 5. Collector/Faraday Pail Capacitance Schematic.

prevent feedback current. The collector/Faraday pail was the primary measurement method utilized in the laboratory; consequently, ground effect feedback current was not discovered until field testing. Figure 6 illustrates ground-current measurement and how feedback current subtracts from measured ground current to produce ground effect, that is, a reduction in ground current and net emitted charge (charge which does not return to the spray assembly plumbing).

The method used to measure drop radius was to collect a given number of drops and measure the volume of collected liquid. The volume per drop is calculated by dividing the volume of collected liquid by the number of drops and using the equation connecting the volume of a sphere

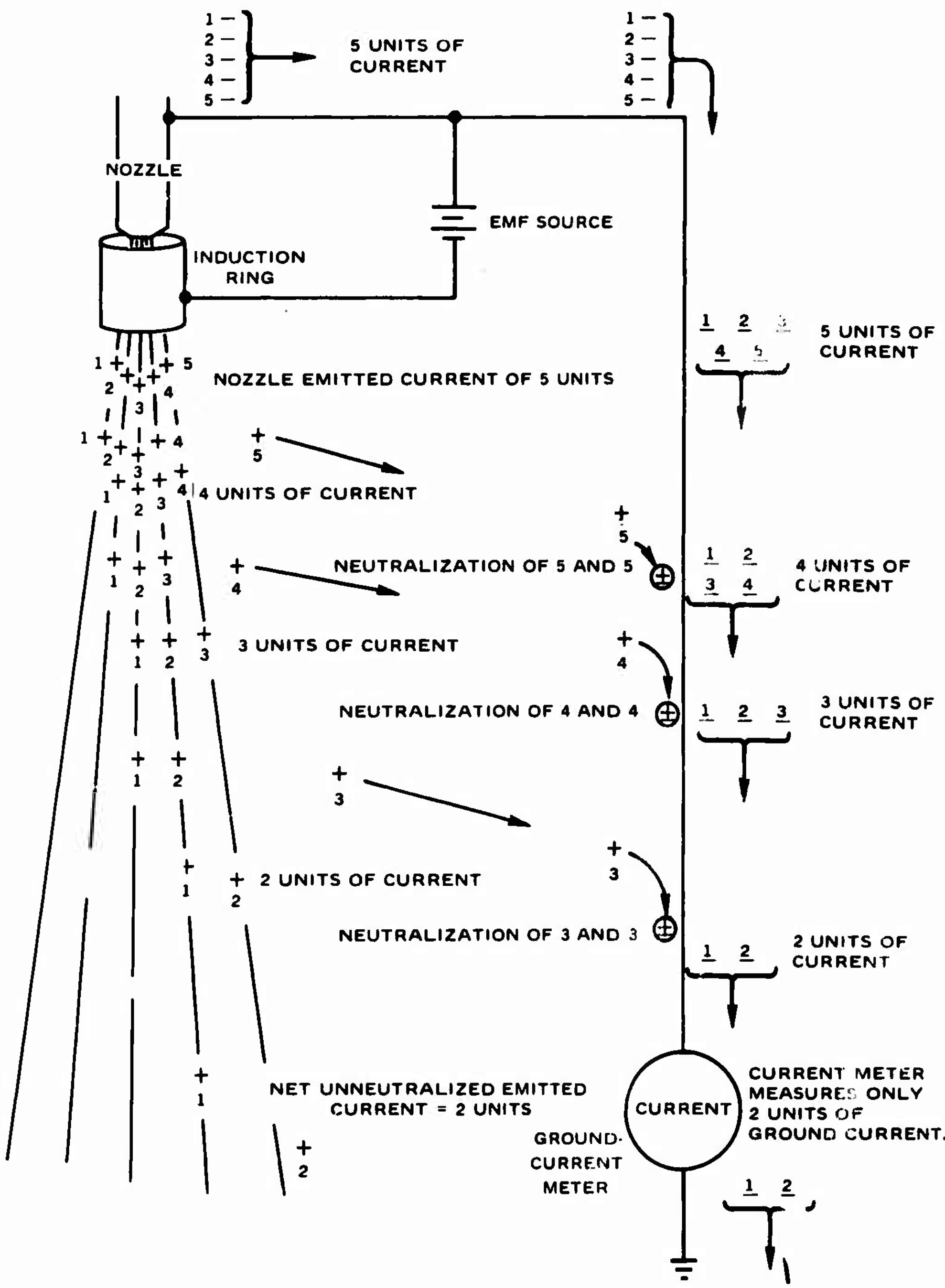


FIG. 6. Ground-Current Measuring Schematic Showing How Feedback Currents Produce Ground Effect.

with its radius ($4/3\ \pi R^3$). There are two sources of error. First, an assumption is implied that all drops are the same size. This is reasonable, since the force of gravity and the orifice of the nozzle remain the same, as does the pressure. It is an indirect method of measurement, however. The second source of error is the assumption that drops are spheres, but the deviation of the drop

shape from a sphere is minimized by the low velocities acquired under the force of gravity over the short distance provided for acceleration between the nozzle and induction ring. Even so, the drop volume does not change; only its shape changes. The shape of the drop as it passes through the ring is the only important factor. The error to a first approximation is the difference in surface area of a sphere and of the actual drop shape at the time it passes through the induction ring. Since a sphere has the lowest surface area per unit volume of any solid, the area of the drops passing through the induction ring is slightly more than it would be if they were perfect spheres.

When a nozzle is emitting a spray instead of individual drops, it is difficult to obtain the size of each drop because they cannot be counted. Hence values for drop sizes in sprays are based upon manufacturer's data. In some cases, the volume of sprayed drops collected in a given time was used to compute spray rates, but the actual size of each drop was not measurable. Slides were used to obtain drop radius, but practical difficulties during laboratory measurements made their accuracy doubtful.

An interesting standard for comparison is the charge per unit volume of sprayed material. In one typical experiment a charge per unit volume of 2.72×10^{12} electrons/cm^3 was produced when 3,000 volts were applied to a charge-drop-producing system under a water pressure of 125 psi. In certain experiments, such as those conducted with air-aspirated nozzles, higher charge per unit volume figures were obtained, but air-aspirated nozzles were abandoned because of additional complexity.

RESULTS

Results of the laboratory investigation are presented in Table 1. These data, which relate charge to the surface area of a drop, are graphically presented in Fig. 7.

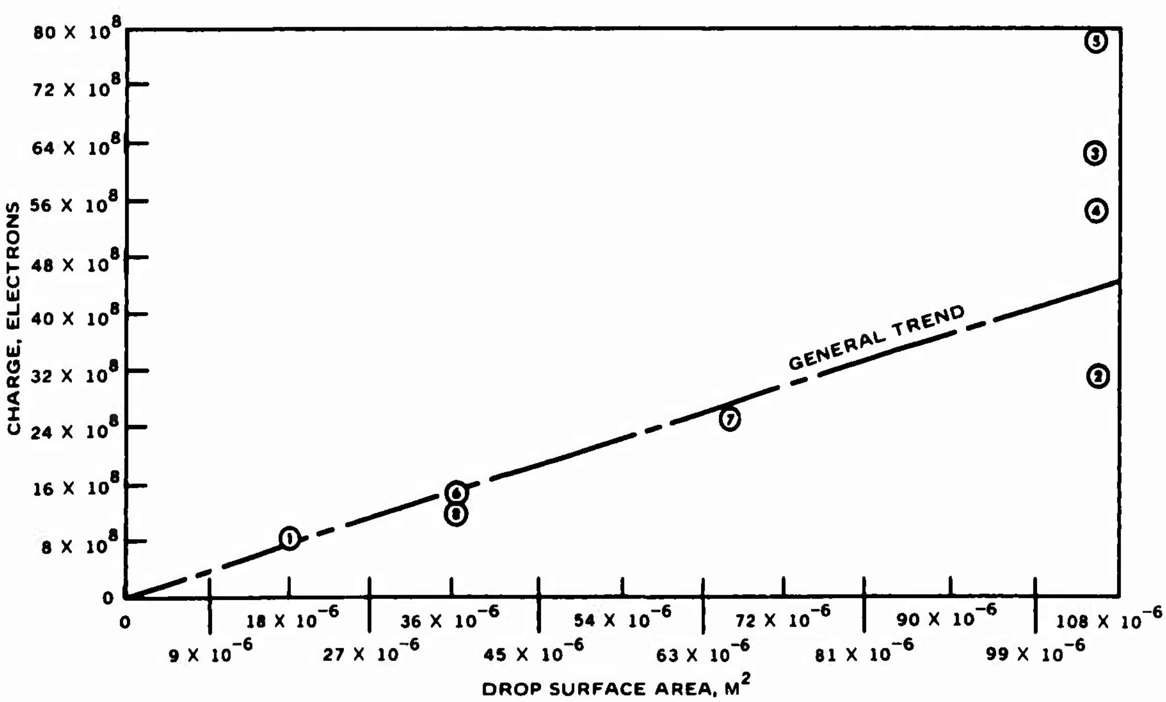


FIG. 7. Laboratory Results; Charge Versus Drop Surface Area. All other factors (emf, charging system geometry, material used in the drops, etc.) not being equal and explained in Table 1 correspond to the numbered plotted points.

TABLE 1. Laboratory Investigation Results.

Plotting point	Charging device	Drop material	Applied emf, V	Drop radius, m	Drop charge, electrons	Charge/surface area, electrons/m^2	Remarks
1	Ring surrounding a nozzle (coffee can nozzle)	Water	3,000	$1{,}200 \times 10^{-6}$	8.12×10^{8}	4.5×10^{13}	This test was conducted indoors using a coffee can with a small hole in the bottom to form the drops.
2	Ring surrounding a nozzle (needle nozzle)	Water	2,000	$2{,}900 \times 10^{-6}$	31.2×10^{8}	2.9×10^{13}	This test was conducted outdoors with only 2,000 volts on the induction ring. The relatively low charge/surface area was also due to ring placement error.
3	Ring surrounding a nozzle (needle nozzle)	Water	3,000	$2{,}900 \times 10^{-6}$	62×10^{8}	5.8×10^{13}	This test, using the same needle nozzle used to obtain point 2 on the graph, resulted in twice the charge/surface area. The high charge/surface area resulted from the application of 3,000 volts, instead of 2,000 volts, and also from more careful positioning of the ring precisely over the break point (i.e., the point in the stream where the drops are electrically severed from the nozzle source/sink), at the end of the nozzle.
4	Ring surrounding a nozzle (needle nozzle)	Water	3,000	$2{,}900 \times 10^{-6}$	54×10^{8}	5.1×10^{13}	Mainly a repeat of the experiment that gave point 3.
5	Ring surrounding a nozzle (conventional nozzle)	Ammonium nitrate plus urea (9:1 solution)	3,000	$2{,}900 \times 10^{-6}$	78×10^{8}	7.35×10^{13}	Apparently, the change of nozzles and of the fluid for forming drops compensated each other, resulting in drops of the same size as in experiments that gave points 2, 3, and 4. The measurement systems used are described in the Measuring Techniques section. This is the highest charge/surface area obtained and is typical of repeats of this particular experiment. Ammonium nitrate/urea 9:1 solution is an excellent conductor, but it is not certain that the consistently high charge/surface areas obtained with it are due to that fact alone, as ample time is allowed by the charging device for even considerably lower conductivity solutions to become charged to their maximum for the geometry used, and the fields developed, in and by the charging system. Other properties of the solutions used could be related to the charge/surface areas obtained by experiments designed for this purpose.

TABLE 1. (Contd.)

Plotting point	Charging device	Drop material	Applied emf, V	Drop radius, m	Drop charge, electrons	Charge/surface area, electrons/m^2	Remarks
6	Parallel plate with 3/16-inch plate spacing	Water	2,000	$1{,}700 \times 10^{-6}$	15.6×10^{8}	4.3×10^{13}	Even at 2,000 volts, occasional arcing occurred. The relatively severe arcing problems associated with the parallel plate charging device could be solved by simple engineering. These models used nylon screws, which protruded between the plates and when wet provided an easy shorting path between plates. The method of maintaining plate spacing should be external and hence without any material between plates.
7	Parallel plate with 1/4-inch plate spacing	Water	3,000	$2{,}300 \times 10^{-6}$	25×10^{8}	3.76×10^{13}	The lowered charge/surface area was due mainly to the increased plate spacing, which more than balanced out the increase in emf in this experiment.
8	Parallel plate with 1/4-inch plate spacing	High-grade detergent oil	3,000	$1{,}800 \times 10^{-6}$	12×10^{8}	3.25×10^{13}	This oil was an excellent insulator, showing greater than 100 megohms between two probes inserted 1 centimeter into the oil, 1/2 centimeter apart.

INDUCTION CHARGING SYSTEM DESIGN

The basic principle that guided the design of the induction charging system used in the field experiment is that of providing as high an electric field as possible between the induction ring and drop for a certain time before the drop is removed from the nozzle and becomes electrically isolated. How long contact between the drop and nozzle has to be maintained in the presence of a high electric field is a function of the resistivity of the drop material. For drops of typical tap water, the time required is only milliseconds. For drops of typical engine oil, the time is about a second. These times were obtained using the laboratory equipment described, with the electric field magnitudes available. They are stated for comparison purposes only with the realization that they are a function of variables that vary between different laboratories and test setups. Included in the variables would be water purity, type of oil and additives used, electric field intensities, etc. The high electric field is obtained by placing an emf across the smallest gap that does not permit arcing. Capacitance between the ring and nozzle is not important, but capacitance between the ring and drop is all-important. Maximizing the latter produces a maximum electric field where it is needed, at the surface of the drop, thus allowing maximum charging of the drop for a given emf between the ring and drop/nozzle combination.

Figure 8 shows the four dimensions of significance in the design of an induction charging system; shown is a nozzle surrounded in the drop formation area by an induction ring. Dimension d_1, which is the thickness of the tubing from which the ring is made, is of minor significance because induction charging is a capacitive process and material thickness has negligible effect on electric field formation. In practice, d_1 is made as thin as mechanical considerations permit. Dimension d_2 has a broad effect on the drop charging process. The smaller the diameter, the higher the electric field for a given emf; however, a limit against ever-smaller diameters exists. Charged drops, while still on the nozzle tend to

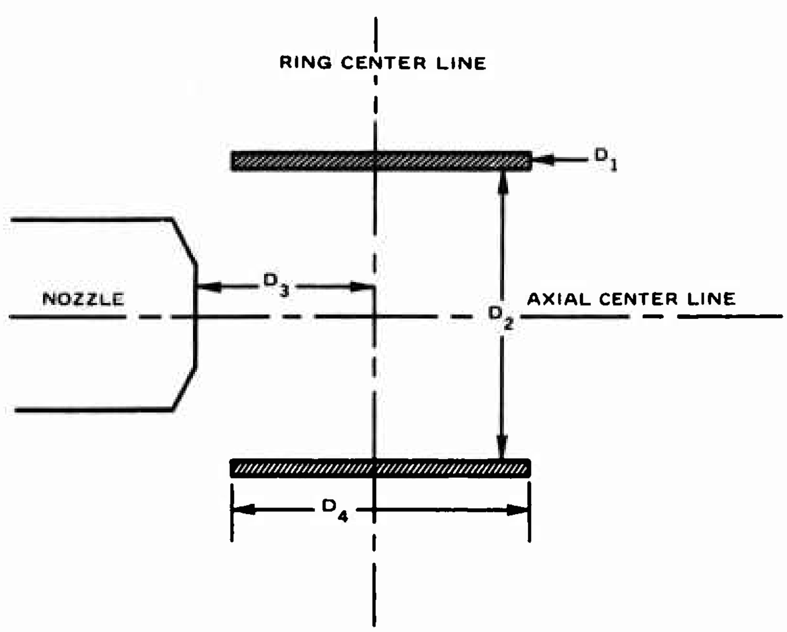
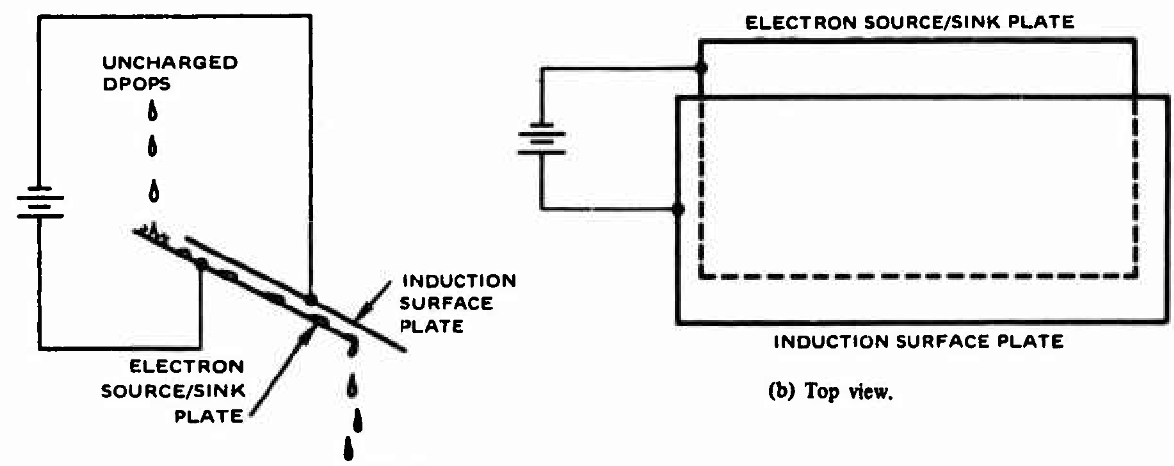


FIG. 8. Induction System Principal Dimensions.

be attracted to the oppositely charged ring and provide short circuit paths if the ring is too small. The practical lower limit of ring diameter is about 3/4 inch. Under ideal laboratory conditions this nozzle combined with a 3/4-inch-diameter ring has a capacity of about 7,000 volts, but once wetted is reduced to about 3,000 volts. In the laboratory the effect of ring diameter on charge per drop was measured by collecting the drops in an insulated pan. The following results were obtained: (1) a ring 6 inches in diameter produced 1 unit of charge (normalized for easy comparison) on a given size drop, (2) a ring 3 inches in diameter produced (on this same scale) 1.6 units of charge on the same size drop, and (3) a ring only 1/2 inch in diameter produced 2.4 units of charge. In practice, d_2 is made as small as arc paths through the drop to the ring will permit, about 3/4-inch diameter being the smallest practical. Dimension d_3 is important and is determined by the location of the electrical "break" point of a stream. The break point for a nozzle that is producing one water drop at a time is at the end of the nozzle. In a stream this break point moves out beyond the end of the nozzle, the actual distance being a function of water pressure, spray pattern, etc. The particular nozzles used (Delavan 30-degree hollow-cone) yielded a spray drop size of 50 X 10^{-6} meter median radius at pressure of 100 to 125 psi. This break point occurs approximately 3/4 inch away from the end of the nozzle, and this is where the center of the ring should be located. In the system constructed, the center of the ring (not the axial center line, but the center line perpendicular to the axial center line; see Fig. 8) was placed 3/4 inch from the end of the nozzle, to provide full field at the stream break point. As a practical point, one useful and easily applied method of determining the break point is the use of an ohmmeter. One probe is placed on the nozzle and the other in the stream. As the probe in the stream is moved along the spray center line a sudden change in resistance will occur in the spray. The effect is fairly sharp, and in the laboratory case, the break point was bracketed to within 1/8 inch. It is recognized that other spray devices and pressures may deliver either a sharper or broader break point. Dimension d_4 should be long enough to guarantee that the break point, which varies slightly, always remains within the ring and hence within the region of high electric field. From this point of view, the ideal ring should extend from the end of the nozzle to several feet beyond the end of the nozzle, thus enclosing every conceivable break point location. A limit against ever-greater lengths exists, however. There is an attraction between the charged drops and the oppositely charged ring, and as the ring is made longer, the amount of drops that intercept the ring increases. It is geometrically evident that the longer the ring, the lower is the off-axis angle required for a drop to intercept the ring. This consideration calls for as short a ring as possible, in order to limit the number of drops that intercept the ring and become discharged as a result. In practice, d_4 was made 1 inch.

An alternate geometry for an induction charging system is as follows. The system, while not adaptable to spraying in its present form, is effective as a gravity-operated drop-at-a-time system. It has an efficient shape, is easily constructed, and was used to charge oil drops. It consists of two parallel plates inclined as shown in Fig. 9. The liquid flowing between the plates has about 1 second to charge, and hence even relatively good insulators like oil can be charged. Two of these parallel plate devices were made, the first with a plate separation of 3/16 inch and the second with a plate separation of 1/4 inch. They were approximately 6 inches wide and 2 feet long. The significant dimensions here are the separation and width of the device. The only significance of the length is the flow rate it permits. The original device with a 3/16-inch separation between plates arced intermittently at 2,500 volts, but was relatively free from arcing at 2,000 volts. Hence, 2,000 volts were used in experiments with this model. Laboratory results using the parallel plate device are summarized in Table 1.



(a) Side view.

(b) Top view.

FIG. 9. Parallel Plate Induction System.

FIELD TESTS

EQUIPMENT

Field tests were conducted utilizing the developed induction charging system and pressurized water delivery system. The lifting apparatus consisted of a manned hot-air balloon (Fig. 10) 60 feet in diameter with a payload capacity of about 1,400 pounds, which had self-contained propane burners (Fig. 11) to provide a controlled supply of hot air. Instrumentation consisted of a ground current recorder and two field mills to measure electric field. Ground currents were continuously monitored on a Sanborn chart recorder while the field mills monitored electric field near the ground in the spray plume. Nonelectrical effects were measured by both slide and impactor drop samplers.

The charged-drop-producing system in its field-ready form (Fig. 12) used 48 Delavan 30-degree hollow-cone nozzles. The nozzles are designed to give a median drop radius of 50 X 10^{-6} meter and a spray rate of 8.8 gal/hr at 125 psi. The induction rings were cylinders 3/4 inch in diameter by 1 inch in length. They were mounted with the edge of the ring 1/4 inch away from the end of the nozzle. This configuration centered the ring over the break point, which was approximately 3/4 inch from the end of the nozzle. During field tests, conical induction rings were substituted for the straight cylinders and were found to be more efficient. The conical induction rings had an angle of approximately 30 degrees, which coincided with the 30-degree nozzle spray pattern; exit openings of 1 1/4 inches; and entrance openings of 3/8 inch. The entrance openings were partially a result of rounding off the edges in the region adjacent to the end of the nozzle (Fig. 13) to discourage arcing between the nozzle and induction ring. Both the cylindrical and conical induction rings were held in place by Teflon holders that slipped over the nozzles. All nozzles combined to produce a spray rate of approximately 6 gal/min. The assembly plumbing, which supported the nozzles, was an octagon (Fig. 12) with sides about 12 feet long, supported by cables, and was 20 feet below the gondola.

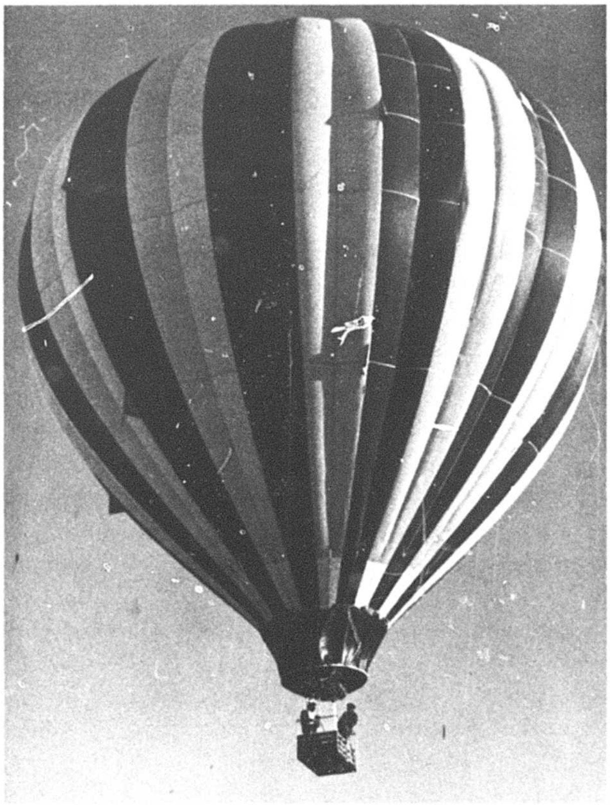


FIG. 10. Hot-Air Balloon and Gondola.

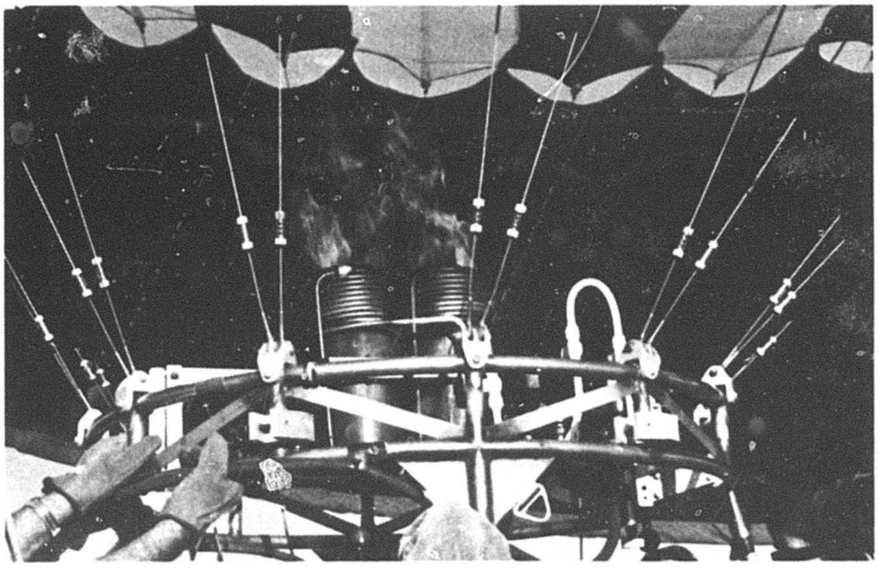


FIG. 11. Hot-Air Balloon Propane Burners.

FIG. 12. Spray Assembly Suspended From Balloon.

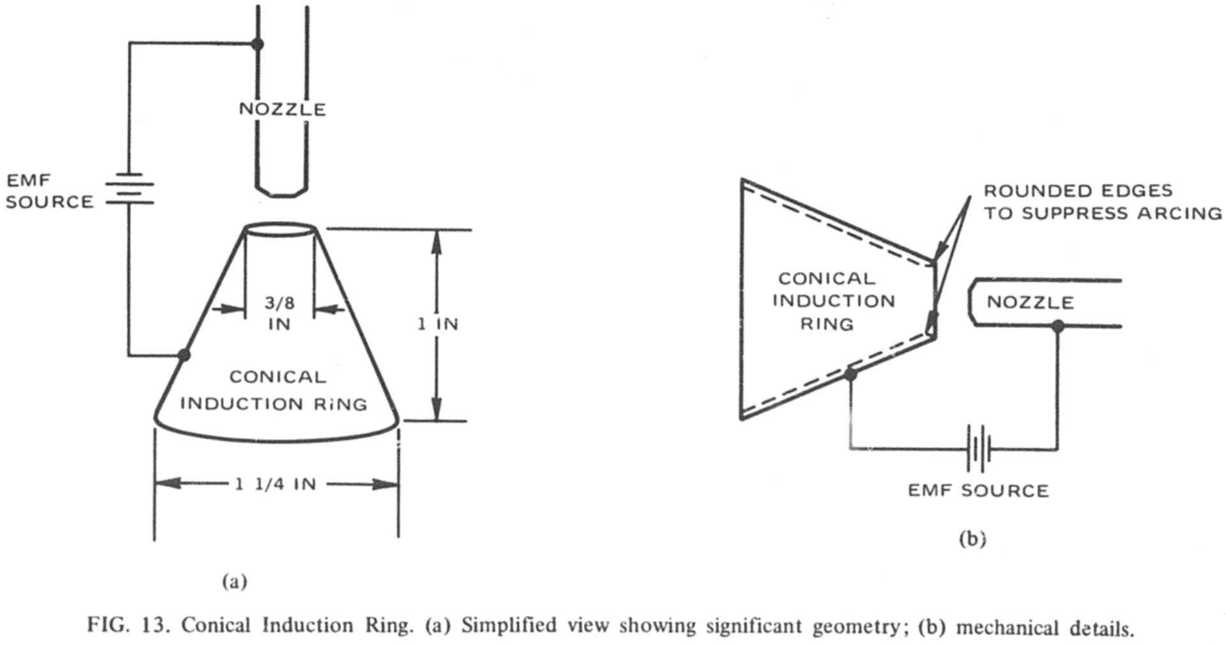


FIG. 13. Conical Induction Ring. (a) Simplified view showing significant geometry; (b) mechanical details.

Twenty-four cables were used, as the plumbing itself was not sufficiently rigid to permit single-, two-, or three-point suspension. A water tank pressurized by compressed nitrogen or helium fed the assembly through moderate pressure water hose. In early experiments, a ground-mounted emf source was used; however, as higher altitude testing became desirable, a portable emf source made up of thirty 90-volt radio-type B batteries was constructed that provided about 2,700 volts when fresh and declined to 2,200 volts after use.

The original field charged-drop-producing system used iron pipe for plumbing, cathode ray tube cable for wiring, and cylindrical induction rings. The rebuilt field system used stainless steel pipe for plumbing and automotive ignition wire for all wiring, and, as noted above, more efficient conical induction rings were substituted for the cylindrical induction rings. Care was taken to ensure that the ignition wire was the wire type rather than the resistance type. In spite of the use of ignition wire that handles 15,000 volts, severe leakage problems at 2,500 volts occurred after several days' exposure to damp weather. To keep the ignition wire away from the plumbing, plastic cup insulators (Fig. 14) were constructed and produced

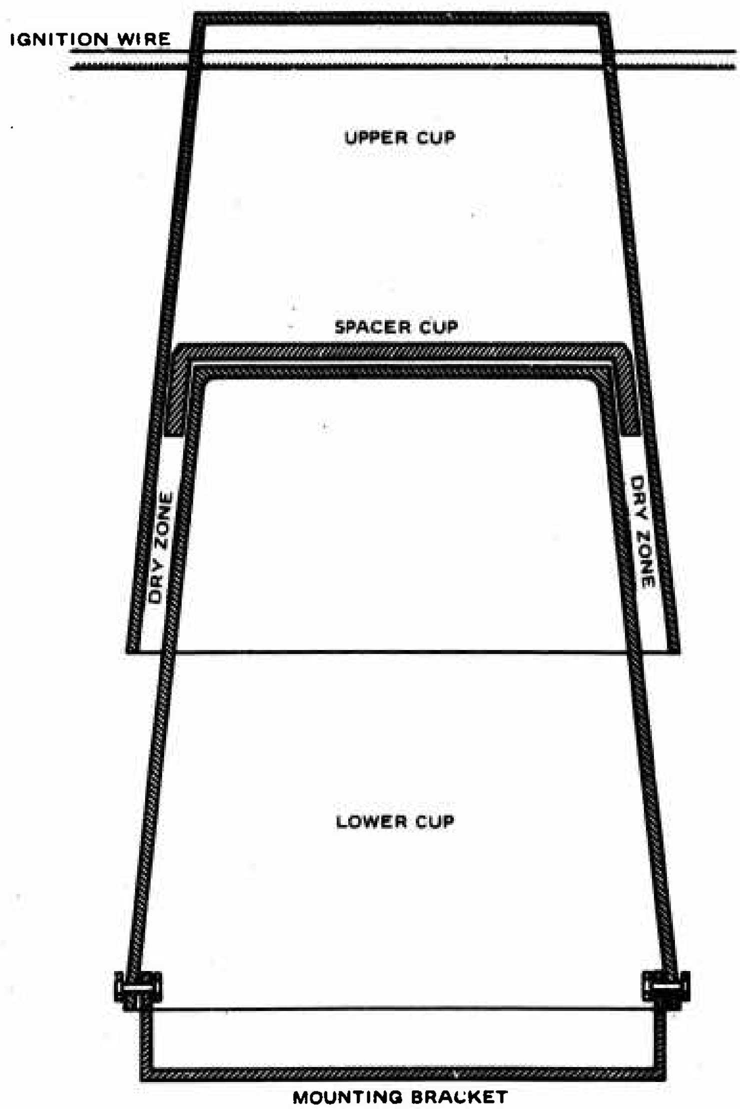


FIG. 14. Cup Insulators. The mounting bracket was bolted to the lower cup and attached to the plumbing by means of hose clamps.

excellent results. The charging system wiring ran through the upper cups, and the lower cups were fastened to the spray assembly plumbing. These insulators are ideal for use in wet weather because of a dry zone between the inner surface of the upper cup and the outer surface of the bottom cup. The upper cup does not touch the lower cup, but is separated from it by a portion of a third cup, which is shown in Fig. 14 as the spacer cup. The dry zone provides reliable insulation in wet weather. Therefore the use of more cups stacked on top of each other, resulting in more dry zones, is suggested.

In the field, the battery pack was originally placed on top of a 1-inch-thick board, but moisture penetrated the board and battery cases. After several hours' use some of the batteries began smoking because of the high emf with respect to ground. The moisture-impregnated board that supported the batteries had permitted sufficient current to pass through the battery case and board to burn up the batteries. The multicup insulators were used to prevent recurrence of these excessive short circuit currents.

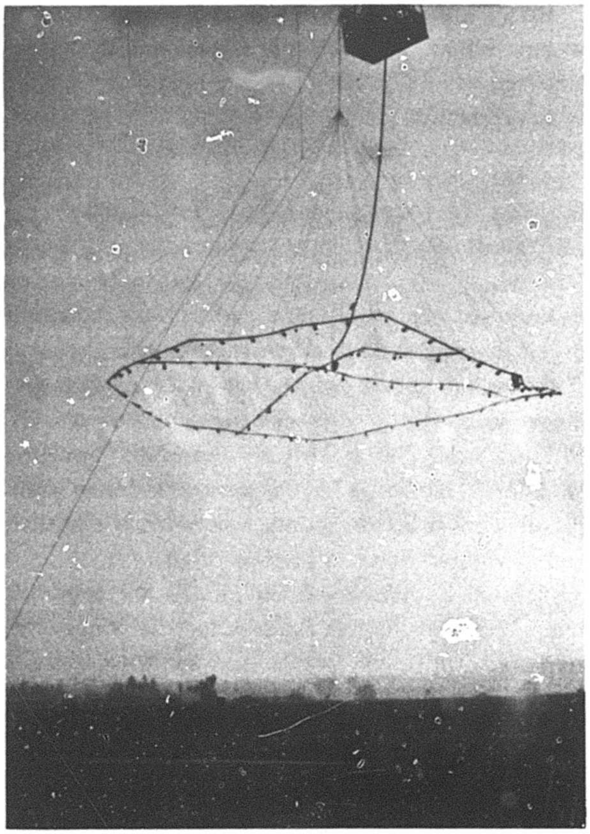


FIG. 15. Flight Test E1B Charged Spray.

FIELD TEST DATA

The principal purpose of the field tests was to determine the effect of charged drops upon a foggy environment. This goal was thwarted by a previously unobserved phenomenon, which was termed "ground effect" (see Appendix A), and the unavailability of warm fog. The field test data presented in this section delineate the chronology of events related to this ground effect and experiments conducted to overcome this problem. Test information, including purpose, equipment, procedures, results, and interpretation, is presented in the following pages.

Flight Tests E1B, E2B, and E3B (13, 14, and 15 September)

Purpose. To check out the spray assembly and the ground-current measuring capability of the measurement van.

Apparatus. Forty-eight-nozzle charged-drop-producing system, ground-current measuring van, and balloon.

Procedure. Attempts to measure ground current were made with the 48-nozzle system emitting charged spray while suspended from the gondola of the balloon (Fig. 15).

Results. No ground current was measured.

Interpretation. None.

Ground Checks Between Tests E1B, E2B, and E3B (14 and 15 September)

Purpose. To locate ground-current measurement problem.

Apparatus. Forty-eight-nozzle system, sawhorses 3 feet high, and measurement van.

Procedure. The forty-eight-nozzle system was suspended from sawhorses 3 feet high while emitting charged spray. Ground current was monitored on these tests.

Results. A ground current of 80 microamperes was measured. A current of 200 microamperes was expected.

Interpretation. None.

Ground Test Prior to Flight Test E4B (17 September)

Purpose. To study the effect of insulation problems on ground-current measurements.

Apparatus. Forty-eight-nozzle system, sawhorses 3 feet high, plastic cups, and measurement van.

Procedure. The system was carefully insulated from the sawhorses by inserting material from plastic cups wherever contact between the system and sawhorses would otherwise occur.

Results. A ground current of 300 microamperes with 2,000 volts on the induction rings was measured while the system was emitting charged spray. This is an expected value based upon laboratory measurements.

Interpretation. None.

Flight Test E4B (18 September)

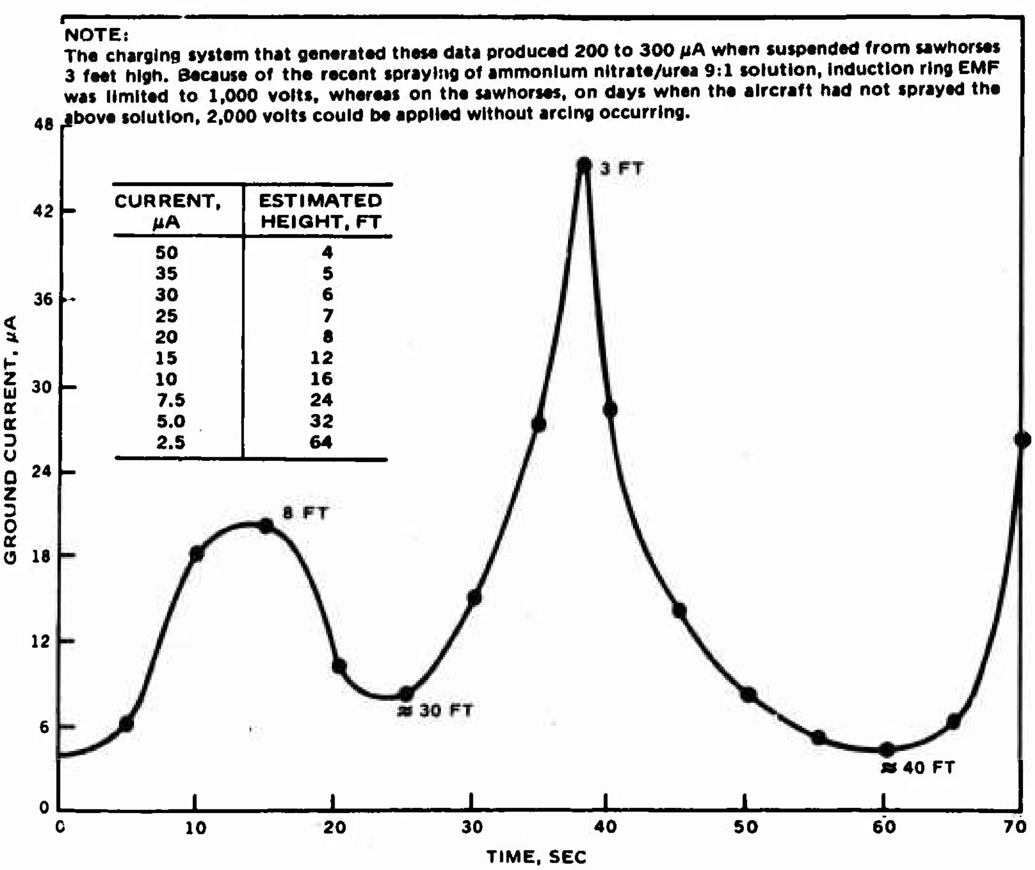
Purpose. To evaluate the circuitry change in the ground-current measurement equipment in the measurement van and to determine if measured ground current is a function of altitude.

Apparatus. Forty-eight-nozzle system, ground-current measurement van, and balloon. A diagram of the electrical measurement system is shown in Fig. 6.

Procedure. While the 48-nozzle system was emitting charged spray, its altitude was varied from practically ground level to altitudes of 100 feet. Ground current was continuously monitored.

Results. Measured ground current decreased as altitude increased. Figure 16 shows the results in graphical form. Field mills measured up to 4,000 V/m.

Interpretation. None.



CURRENT, μA	ESTIMATED HEIGHT, FT
50	4
35	5
30	6
25	7
20	8
15	12
10	16
7.5	24
5.0	32
2.5	64

FIG. 16. Flight Test E4B: Ground Current Versus Altitude.

Screen Grid Immunity Test (23 September)

Purpose. To determine susceptibility of the charged-drop-producing system to external influences.

Apparatus. Single-nozzle system (Fig. 17), 1/4-inch mesh wire screen, and ground-current measurement van.

Procedure. A screen grid made of 1/4-inch wire screen was placed several inches in front of the induction ring as shown in Fig. 18. Ground current was monitored while the nozzle was emitting charged spray. Four configurations were tried: (1) with screen grid charged to +500 volts, (2) with screen grid charged to -500 volts, (3) with screen grid floating, and (4) with screen grid tied to ground through the spray assembly plumbing and hence electrically above the ground-current measuring van.

Results. No change in ground current was noted in any of the above configurations.

Interpretation. The test verified the immunity of the charged-drop-producing system to the presence of screen grids nearby, grounded or otherwise, and hence the immunity of the charging system to nearby grounds. The charged-drop-producing system showed no ground current variation, even with a total charge of 1,000 volts on the screen grid.

Since the test indicated that no change in spray current occurs, it was hypothesized that some leakage mechanism was responsible, and this led to the screen grid ground return test. The ground-current meter, or its equivalent, the ground-current measurement van, was always physically and electrically adjacent to the actual ground point, which was a length of pipe in the earth, and this is why the feedback current always returned to ground via the spray assembly plumbing above the ground-current meter, where it would subtract from ground-current readings, rather than below the ground-current meter.

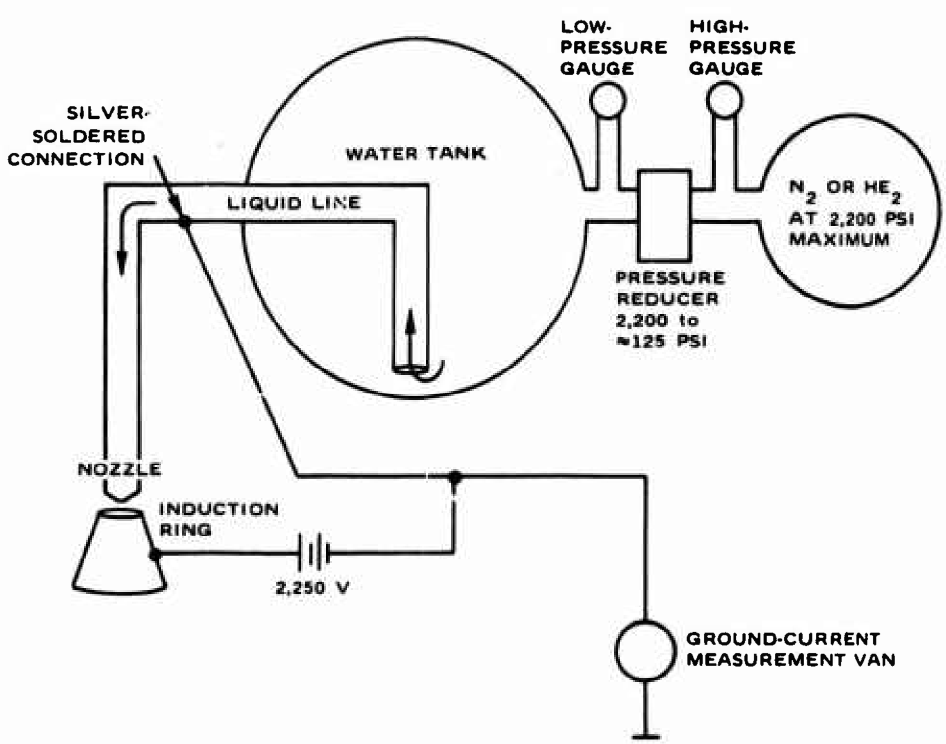


FIG. 17. Single-Nozzle Charged-Drop-Producing System Showing Plumbing and Electrical Arrangement.

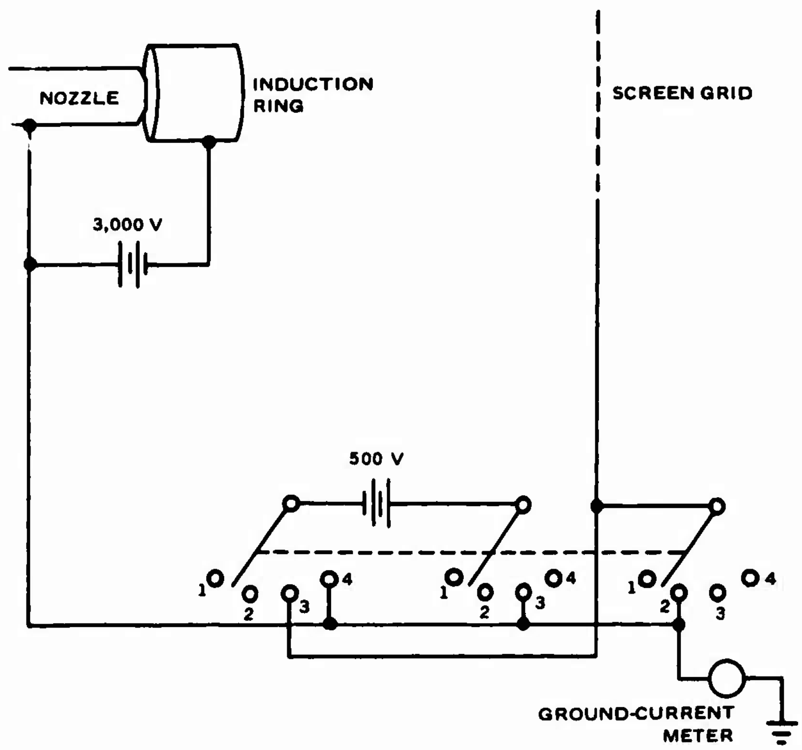


FIG. 18. Screen Grid Immunity Schematic. A 3-pole, 4-position switch is used as a device to simplify the diagram rather than to draw four separate diagrams. With switch in position 1, screen grid is floating; with switch in position 2, screen grid is grounded (upstream of the ground current meter); with switch in position 3, screen grid is +500 volts with respect to ground; with switch in position 4, screen grid is −500 volts with respect to ground.

Screen Grid Ground Return Test (23 September)

Purpose. To direct the hypothesized feedback current directly to ground, bypassing the current around the ground-current measurement van.

Apparatus. Single-nozzle system assembly, 1/4-inch mesh wire screen, and ground-current measurement van. Figure 19 shows this arrangement.

Procedure. The screen grid was placed several inches in front of the charged-drop-producing system, and ground current was measured with the screen grid returned to ground first above and then below the ground-current meter (ground-current measurement van).

Results. With the screen grid returned above the ground-current measurement van, ground current was 0.5 microampere; with the screen grid returned directly to ground and hence below the ground-current measurement van, ground current was 4 microamperes.

Interpretation. The idea of the screen grid ground return test was to direct the feedback current so that it would not affect the ground-current meter (or measurement van); this was done by routing all current directly to ground, below the measuring apparatus. As a matter of interest, this could have been accomplished (theoretically) by placing the ground-current meter adjacent to the nozzle, but physically this was not feasible. Therefore, rather than move the ground-current measuring apparatus above the region where the feedback current

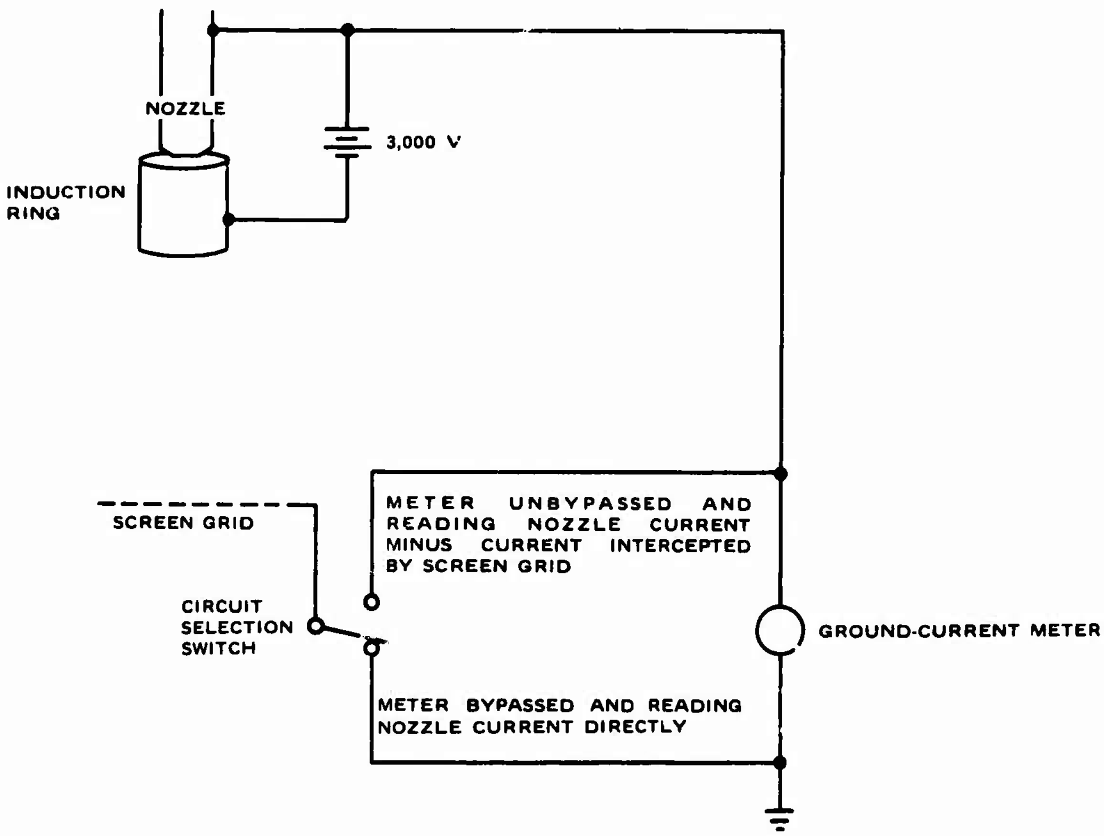


FIG. 19. Screen Grid Ground Return Test Schematic.

intercepts the spray assembly plumbing, the region of interception itself was moved below, and hence around, the ground-current measuring apparatus. The screen grid was placed several inches in front of the charged-drop-producing system, and hence it intercepted nearly all of the spray current and bypassed it either directly to ground or through the ground-current measuring apparatus to ground, making it easy to compare the meter readings for each case. A ground was always nearby whether it was the spray assembly plumbing or this screen grid; hence the screen grid's introduction provides a minimum of disturbance electrically. As stated, the screen grid immunity test verified the immunity of the charging system to external screens, grounded or otherwise, near the charging system. The important feature of this screen grid was its ability to intercept nearly all of the spray current, and in doing this it left little charge further down the spray plume to leak off to the spray assembly plumbing. The net result of this interception of nearly all of the charges was that nearly all of the feedback current was eliminated, without affecting the nozzle current. This permitted the determination of whether ground effect was due to a feedback current to the spray assembly plumbing. Since ground current is nozzle current minus feedback current and since feedback current is eliminated by the grounded screen grid (when it is bypassed directly to ground), ground current equals nozzle current. This nozzle current, unaffected by the screen grid, is the same nozzle current that existed before introduction of the grounded screen grid. We know, therefore, whether the reduced ground-current reading observed before the introduction of the screen grid was due to a reduction in nozzle current or the presence of feedback current. The results of the screen grid

ground return test (where only 0.5 microampere was observed with the screen grid intercepted current returned above the ground-current measurement apparatus as against 4 microamperes when the screen grid intercepted current was returned directly to ground) indicated that a leakage, or feedback current, in this case about 3.5 microamperes, was subtracting from the ground current readings. It is understood that some of the spray charge was not intercepted, permitting some feedback current to the spray assembly plumbing, even when the interception screen grid was grounded, and thus the 4-microampere reading is probably a little low. This would also account for the 0.5-microampere reading obtained when this screen grid was returned above the ground-current measurement van. It appears that charging system current is not reduced, but that feedback current to the spray assembly plumbing is increased as spray assembly distance from the earth is increased.

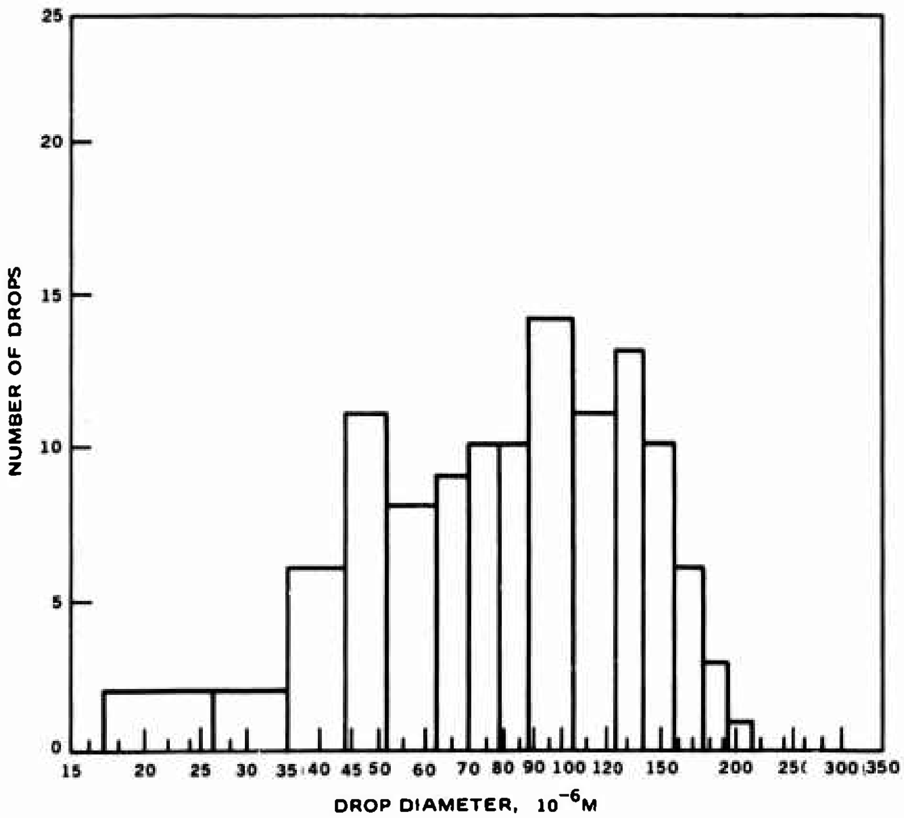
Induction Ring Geometry Test (27 September)

Purpose. To compare drop spectra and nozzle current obtained using cylindrical and conical induction rings.

Apparatus. Conical and cylindrical induction rings, single-nozzle system, and ground-current measurement van.

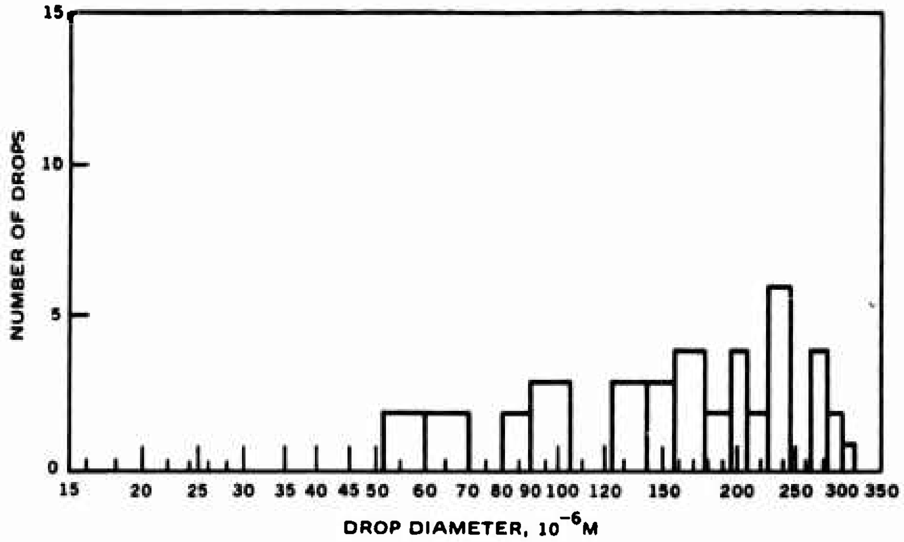
Procedure. Ground-current measurements were made with both conical and cylindrical induction rings. Figure 13 shows the details of the conical induction ring assembly. Drop spectra data were obtained with the conical induction ring only. The drop spectra data also reflect evaporation of drops between their exit from the nozzle and interception by the slides.

Results. Drop spectra data obtained with the conical induction ring are shown in Fig. 20a, b, and c. Because of the small number of drops counted, there is doubt about the data's absolute

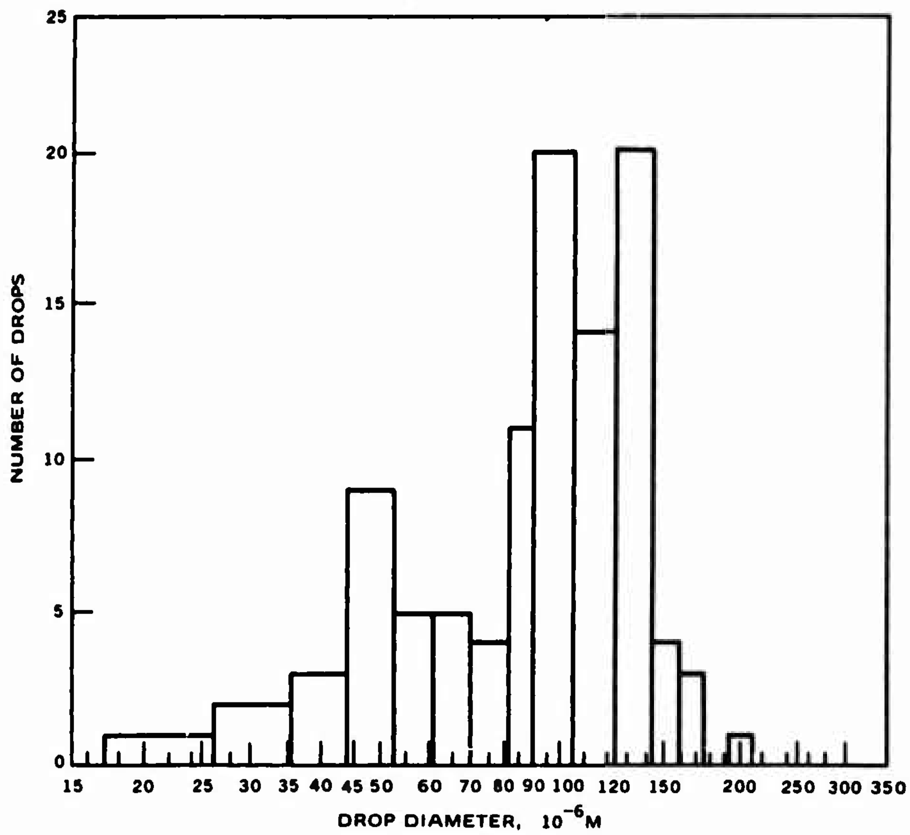


(a) Number of drops versus drop diameter (charged 100 psi).

FIG. 20. Drop Spectra Data Obtained With Conical Induction Ring.



(b) Number of drops versus drop diameter (charged 60 psi).



(c) Number of drops versus drop diameter (uncharged 100 psi).

FIG. 20. (Contd.)

validity. In the field, using either induction ring, the drop spectra varied from the manufacturer's data.

Interpretation. The cylindrical ring worked well at a fixed pressure, but as pressure varied, the spray pattern varied. At certain pressures, a relatively large number of drops hit the induction ring and substantially alter the drop size distribution, even though the cylindrical induction ring may work well at other pressures. The drops intercepting the induction ring are discharged, subtracting from the spray current. A conical induction ring, properly shaped to follow the spray cone angle, is a great improvement in that it preserves the nozzle drop spectra, since the drop trajectories run parallel to the cone-shaped surface rather than intercepting it. The conical induction ring has the additional advantage of permitting placement of the induction surface closer to the water in the spray, thereby increasing the capacitance between the induction ring surface and the drop surface. Because of the combination of the freedom from spectra alterations caused by drops intercepting the ring and the increased capacitance between the induction ring surface and drop surface, worst-case (for the conical induction ring) improvements of 25% in current were noted. Simply stated, it is ideal to have the surface of the induction ring conform as closely as possible to the spray pattern of the nozzle. This is another way of saying that the capacitance between the induction ring surface and the drop surface should be maximized to provide a maximum ratio of electric field to applied emf. As noted above, however, improvement in drop spectra obtained by eliminating the collision of drops against the induction ring surface was an important factor in the superiority of the conical over the cylindrical induction ring. With the conical induction ring the current increased approximately linearly with pressure up to about 100 psi, above which the increase of current with respect to an increase in pressure was low.

Single-Nozzle With Blower Ground Test (28 September)

Purpose. To determine whether use of a blower will increase ground current by preventing the free charges, or charged particles, from returning to the grounded spray assembly plumbing.

Apparatus. Single-nozzle system using conical induction rings and sawhorses 8 feet high, balloon inflator blower, and ground-current measurement van. Figures 21 and 22 illustrate this experiment.

Procedure. Ground current was measured with the blower on and off while a charged spray was being emitted. Minus 2,250 volts were applied to the induction ring.

Results. With the blower off, measured ground current was 2 microamperes; with the blower on, measured ground current was 4.5 microamperes.

Interpretation. The fact that wind had some effect on nozzle current during single-nozzle experiments suggested the use of a mechanical method to keep the charges away from the spray assembly plumbing. This method was successful and suggested the experiment conducted on Flight Test E10B.

Evaporation Retardant Spray Test (1 October)

Purpose. To retard evaporation of sprayed charged drops and determine whether this reduces feedback current.

Apparatus. Single-nozzle system, 1 cm^3 each of two heavy alcohols, $C_{10}H_{21}OH$ and $C_{16}H_{33}OH$, dissolved into 100 cm^3 of C_2H_5OH, with 30 cm^3 of this solution added to the partially filled 6-gallon spray tank.

Procedure. Ground current was measured while the single-nozzle system emitted a charged spray of the above alcohol/water solution.

Results. No increase of ground current was noted over what we attained with plain water.

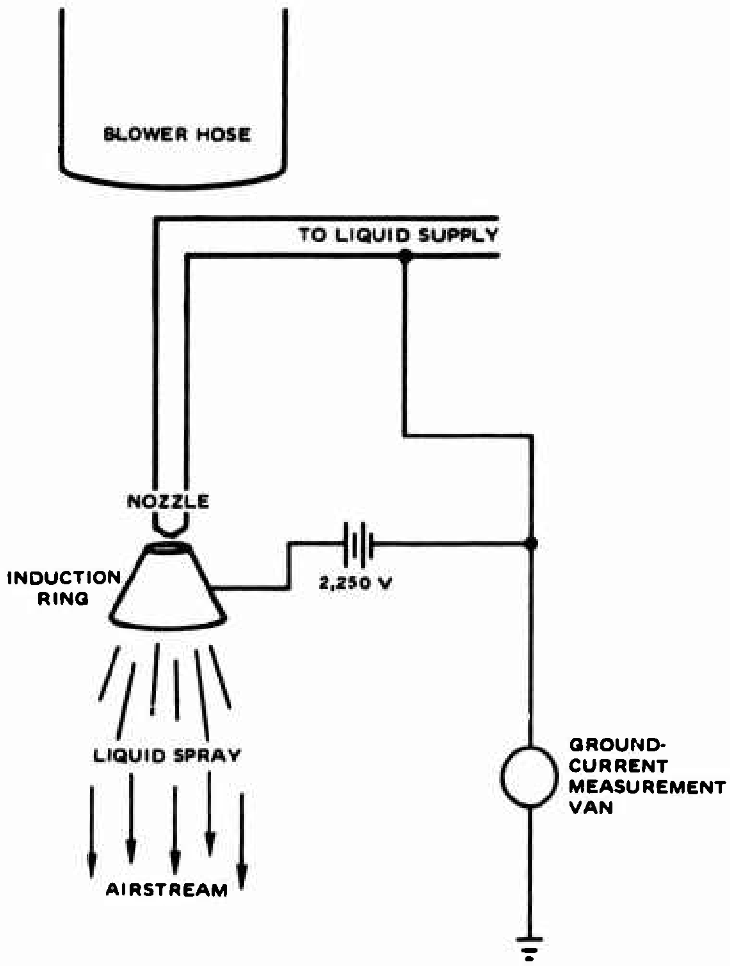


FIG. 21. Single-Nozzle With Blower Ground Test Schematic. Source of moving air is the balloon inflator.

Interpretation. The test was designed to eliminate, o cut back, evaporation and thus to reduce the feedback current, if indeed charged residues left by evaporated drops were the feedback current vehicle. The failure to observe an increase in ground current using the low evaporation heavy alcohol/water solution indicated that residues of evaporated drops were not responsible.

Mapping of Charges Test (1 October)

Purpose. To further establish the existence of, and the paths followed by, free charges, or charged particles, in the vicinity of the spray.

Apparatus. Single-nozzle system, using conical induction rings; charge detector fashioned from a Keithley Type 603 differential electrometer vacuum tube emf meter shunted by 10^9 ohms and

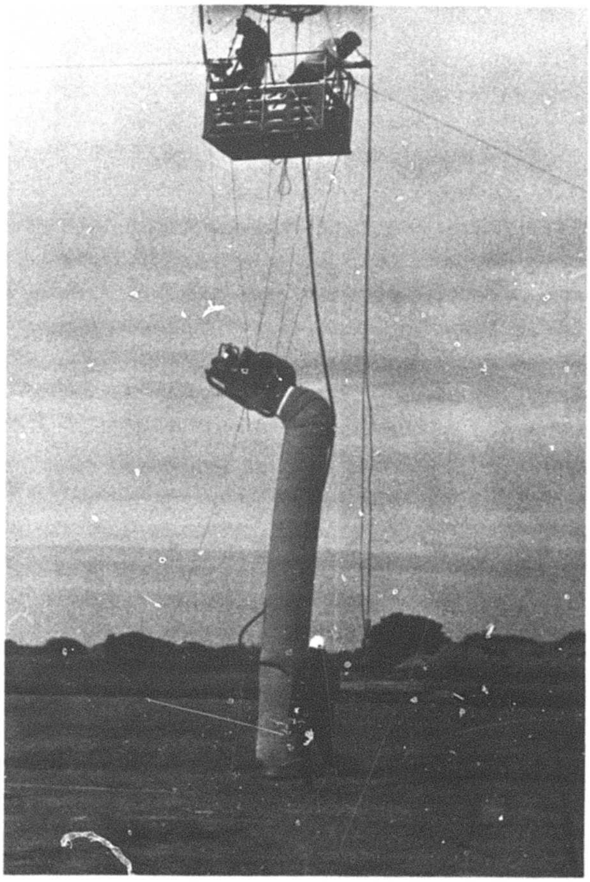


FIG. 22. Single-Nozzle With Blower Ground Test Layout.

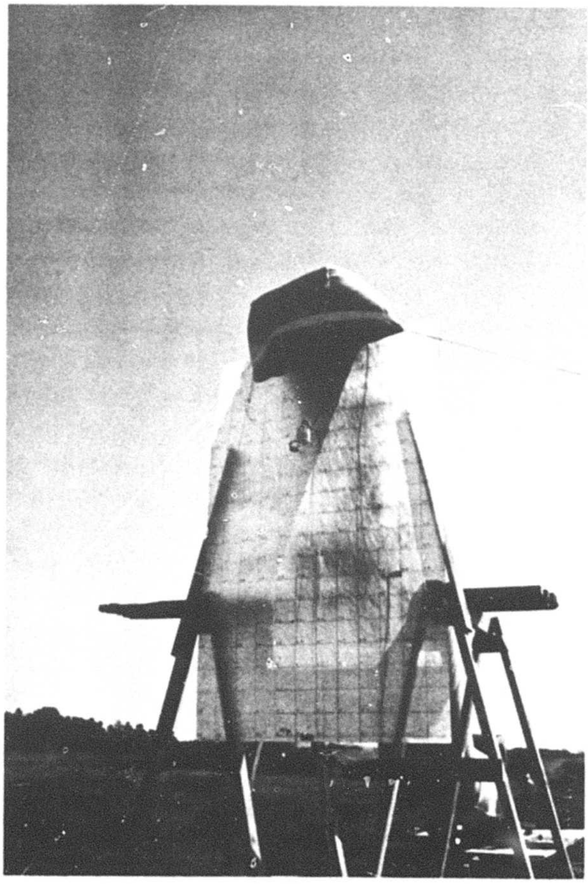


FIG. 23. Mapping of Charges: Experimental Setup.

electrically connected by a long cable (culminating in an insulating glass rod for handling by grounded people) to a brass sphere 3/8 inch in diameter; ground-current measurement van with Sanborn chart recorder channel reserved for measuring current intercepted by the charge detector; and 8- by 4-foot fiber-glass sheet ruled in rectangular coordinates 10 centimeters square and placed behind the nozzle/induction ring (Fig. 23) combination. Figure 24 shows the experimental layout.

Procedure. Current intercepted by the charge detector was measured with both emf and water off, with emf on and water off, with emf off and water on, and with both emf and water on.

Results. Only with both emf applied to the induction ring and the water on (with the nozzle emitting charged spray) were free charges, or charged particles, detected. Intercepted current versus sphere probe position was plotted and the results mapped. The results of mapping are given in two slightly different manners in Fig. 25 and 26. Wind modified the pattern.

Interpretation. This test was performed to obtain further information on feedback current phenomenon. A free charge detection system was built as described in the experiment and used for mapping the feedback current path. The current appeared to follow smooth, discontinuity free paths between the charged spray and the assembly plumbing. The feedback charge per unit volume decreased as the probe was moved further from the charged spray; however, some charge was detected as far away as 2 feet from the spray

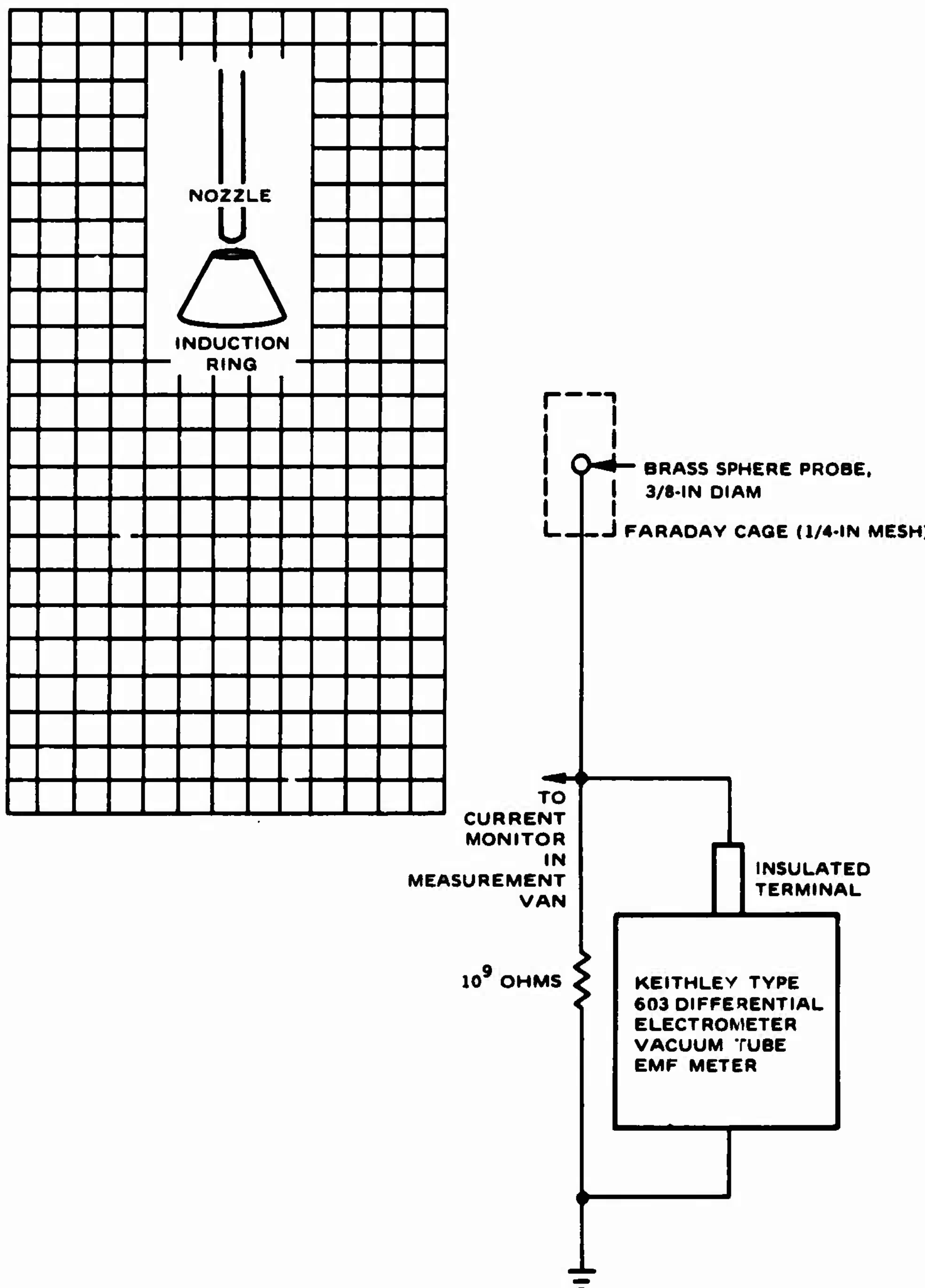


FIG. 24. Mapping of Charges: Experimental Schematic.

plume. This test indicated the existence of floating charges that were apparently not visible water drops, in the vicinity of the spray, and showed the charge flow pattern. Interestingly, wind appears to modify the flow patterns, demonstrating the fact that something that has a force exerted on it by moving air is carrying the charge.

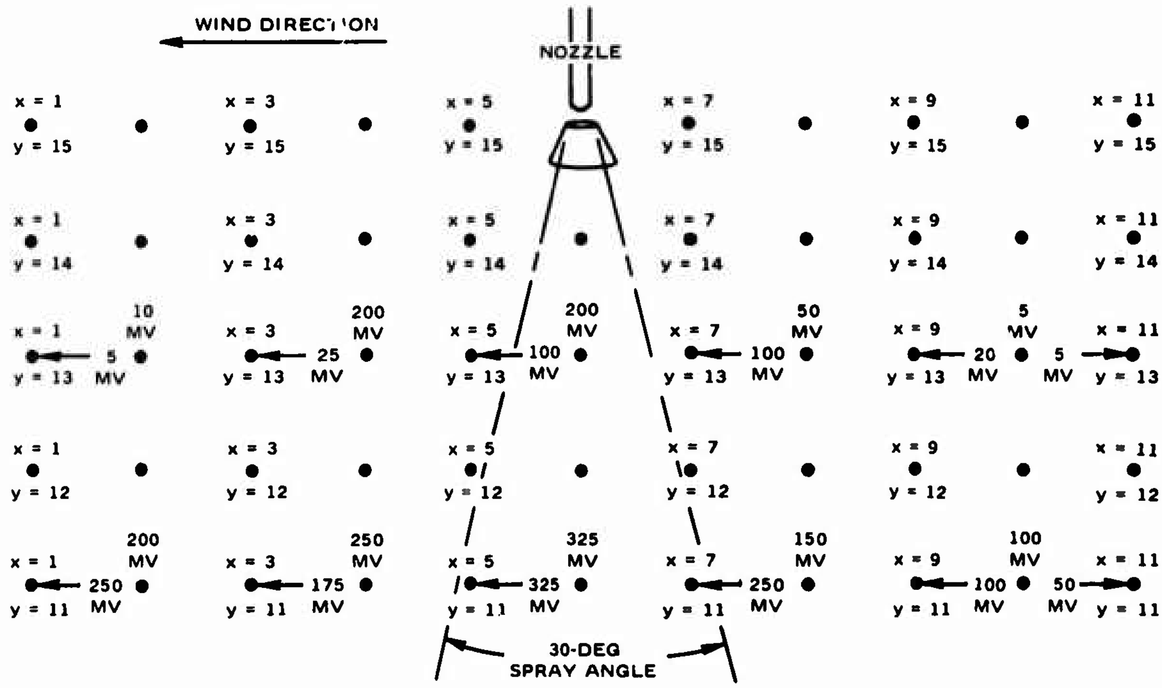


FIG. 25. Mapping of Charges: Current Results. The nozzle is located at x = 6, y = 15, and the coordinates are 10 centimeters square. The emf figures were obtained from the Keithley Type 603 differential electrometer vacuum tube emf meter shunted by 10^9 ohms. The conversion factor is 10^{-12} A/mV.

Flight Test E10B: Multinozzle With Blower (20 October)

Purpose. To determine effectiveness of a blower at higher altitudes.

Apparatus. A specially constructed nine-nozzle system using conical induction rings surrounded by a galvanized sheet metal shroud to channel air from a feed hose about 1 1/2 feet in diameter down over the nozzles. The other end of the feed hose was attached to the balloon inflator. The ground-current measurement van and balloon were also used. A photograph of the test is shown in Fig. 27.

Procedure. With the nine-nozzle system emitting charged spray and the balloon inflator on, the system altitude was varied from practically ground level to approximately 100 feet.

Results. The current decreased with altitude, but not as rapidly as without a blower. Results are shown in graphical form in Fig. 28.

Interpretation. This experiment showed that the use of a blower did tend to reduce feedback current at lower altitudes. At higher altitudes the blower was not sufficient to keep away the emitted charges. Apparently, the charged particles would migrate laterally out of the wind created by the inflator blower and travel back up outside of the windstream to the grounded plumbing of the spray assembly. It might be said that a point of no return for each drop exists between the spray assembly plumbing and the earth. Below this point of no return, the charged particles are attracted by the earth more strongly than by the spray assembly plumbing, and therefore they move on to earth. Above this point of no return, the charged particles are attracted more strongly by the spray assembly than by the earth, and hence they return to the assembly. For sufficiently low altitudes, use of a blower pushes more charged particles below this point of no return and reduces feedback current. At sufficiently high altitudes, however, the point of no return is so far away from the spray assembly that the charged particles migrate out of

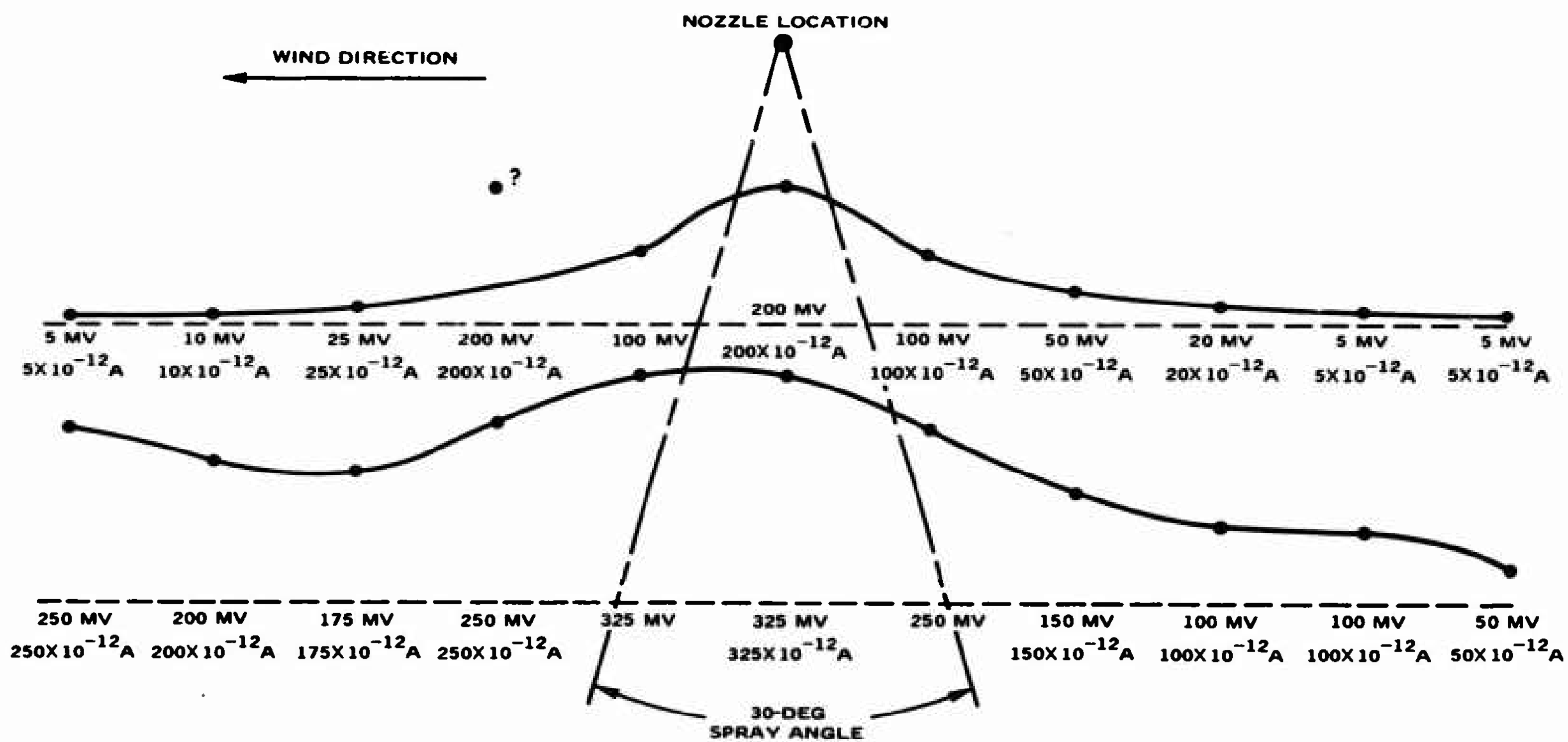


FIG. 26. Mapping of Charges: Intercepted Current Versus x Coordinate for Two Different y Coordinate Levels. Sources of error: Measurements were taken in sequence, not simultaneously, and hence wind velocity varied between measurements. The question-marked data point was possibly an operator error; it is included on the small chance that it could be significant.

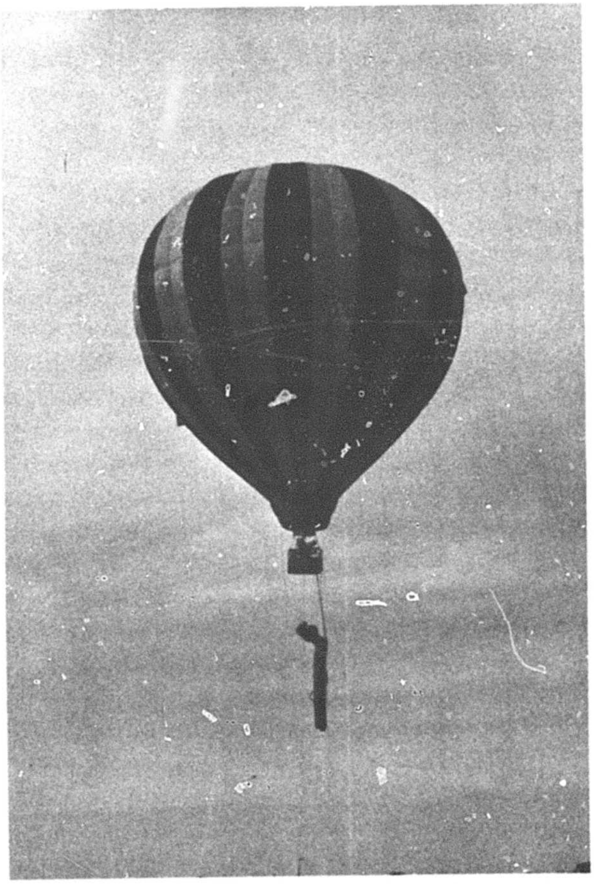


FIG. 27. Nine-Nozzle System With Blower.

the airstream generated by the balloon inflator before the point of no return is reached, with the effect that feedback current is as high as before, only it has a longer path length. Without the blower, the ground effect was strong only at about 10 feet altitude, whereas with the blower, the ground effect was delayed somewhat until about 30 feet altitude had been reached. A more specific comparison can be obtained by comparing Fig. 16 and 28, keeping in mind that Fig. 16 was taken with a 48-nozzle system and Fig. 28 with a special air-blown nine-nozzle system with 2,200 volts on the induction ring. Current per nozzle is the significant quantity in the comparison.

This experiment showed that the mobile charges, or charged particles, could be blown away by mechanical means but that eventually they would find their way back to the spray assembly plumbing if no part of their trajectory approached close enough to earth to make it more attractive than the spray assembly plumbing. In fog, it is anticipated that there should be two effects, both of which would lessen return to the spray assembly plumbing: (1) Contact of the charged drops with fog drops would rapidly decrease the charge per unit mass, thus lessening the attractive force to the spray assembly plumbing. (2) As the

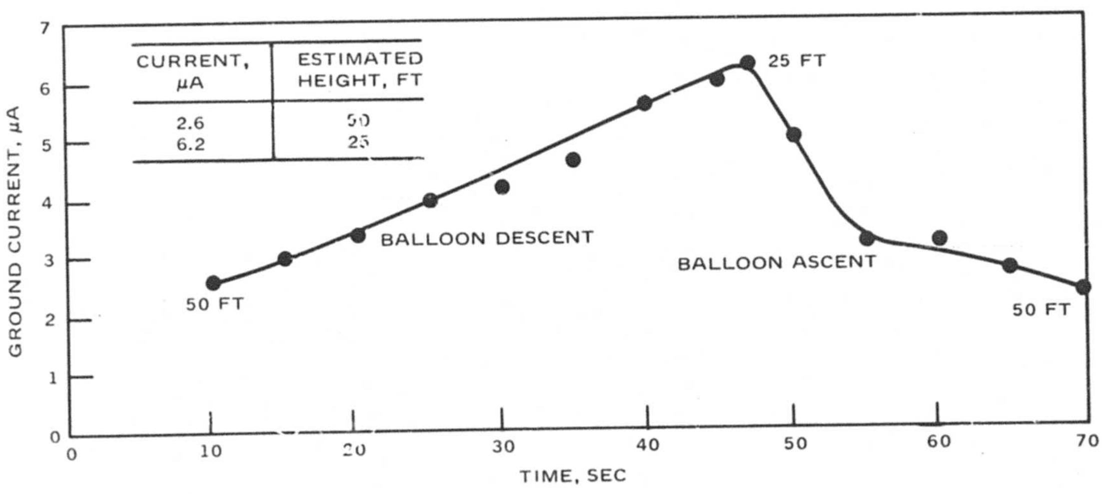


FIG. 28. Flight Test E10B: Ground Current Versus Altitude (With Time as Common Parameter).

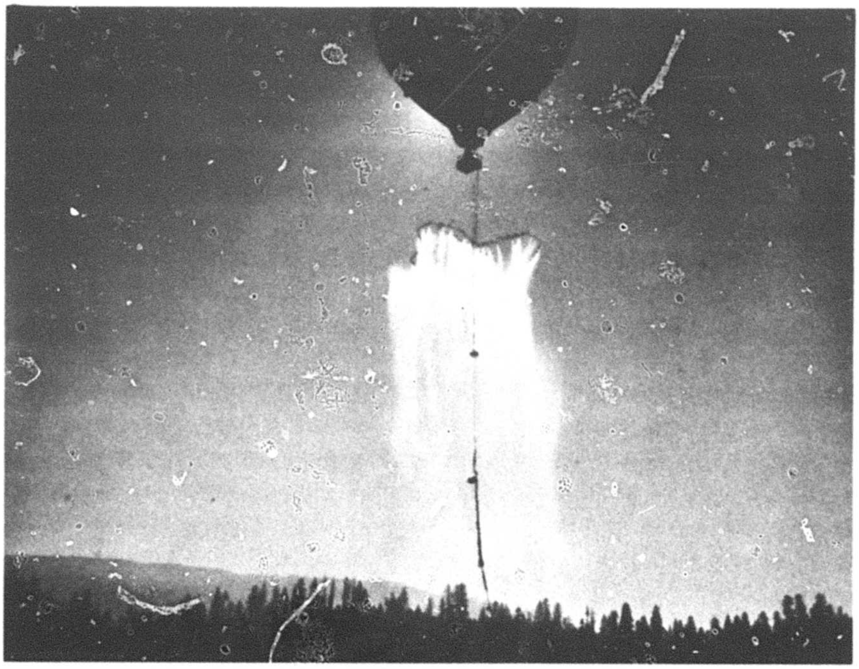
mass of the charged drop would increase, the gravitational force would substantially alter the return rate.

Redwood Valley Tests (24 October–5 November)

Several flight tests were made in Redwood Valley (Fig. 29), a location selected on the basis (from past weather observations) of less wind and more fog than is usually experienced at Arcata. Generally, no new data were obtained; however, spray plume shape changes were again seen corresponding to application and removal of emf on the induction rings. On one of these tests, it was noticed for the first time that drops were rising and intercepting the balloon (Fig. 29c), giving visual verification of the existence of the electrical forces that produce ground effect.

(a) No spray.

FIG. 29. Redwood Valley Tests.



(b) Uncharged spray.

(c) Charged spray, showing drops rising and intercepting balloon.

FIG. 29. (Contd.)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions herein are based on project testing and do not necessarily imply that similar results can be achieved elsewhere. Before any such extension is attempted, consideration must be given to further refinement of techniques and technology related to charged-spray fog-dispersal techniques.

CONCLUSIONS

1. A charged-drop-producing system was developed that adequately produced charged water drops.

2. The induction charging system helped to significantly reduce the number of finer particles ($< 10 \times 10^{-6}$ meter radius) with respect to the median spray drop of 50×10^{-6} meter radius; thus, eliminating possible fog enhancement by these fine particles.

3. The hot-air balloon is an excellent weather modification research tool. Its ability to move with the air mass offers opportunities for quantitative measurement difficult to obtain in any other manner.

4. Conical induction rings offer better charging results than do cylindrical induction rings in the field.

5. The experiments dramatically demonstrated the ability to electrostatically separate particles in open air.

6. The use of charging systems to clear large areas appears to be worthy of further research and is discussed in detail in Appendix B.

RECOMMENDATIONS

1. Laboratory studies to develop a more refined system for separating fine particles from spray drops should be initiated prior to another electrostatic field experiment.

2. The hot-air balloon should be utilized as an atmospheric weather modification research tool for future research programs.

3. Theoretical and laboratory studies should be conducted regarding:

   a. Collection efficiency of drops

   b. Charging to Rayleigh limit

   c. Particle size distribution

   d. Electrostatic attraction of large groups of drops

4. A corona charging system should be developed and its effectiveness compared with the induction charging system.

Appendix A

GROUND EFFECT

An interesting question is that concerning the effect of the earth's natural field on charged drops. Generally, the earth's natural field is positive-going with respect to altitude, and for calculation purposes fields of 100 V/m, which is typical of fair weather, and of 1,000 V/m, a possible level for fog, are assumed. The drops could be forced down faster than gravity alone would drive them or could be given increased tendency to remain up, depending on whether they were made positive or negative, provided that they have drifted enough horizontally to be out of the high local field generated by the charged-drop-producing system.

Given: Drops with a 1×10^{-6} meter radius and a charge-to-surface-area ratio similar to that obtained in the laboratory. This gives a charge of slightly over 500 electrons, a figure not directly verifiable with measurements, but an interpolated extension of the chart of Fig. 7. A drop with a radius of 1×10^{-6} meter has a volume of 4.2×10^{-18} m^3. If it is water, it has a mass of 4.2×10^{-15} kilogram and a weight of 4.1×10^{-14} newton. In a field of 100 V/m the electrical force on this drop is 100 newtons per coulomb times 8×10^{-17} coulomb (which is 500 electrons), which equals 8×10^{-15} newton. Thus, for a drop with a radius of 1×10^{-6} meter charged to 500 electrons and suspended in a 100 V/m field, the ratio of gravitational force to electrical force is 4.1×10^{-14} newton (gravitational) to 8×10^{-15} newton (electrical) or 5 to 1. Under these conditions, the fall of the drops would be slightly retarded. In a field of 1,000 V/m, however, electrical force exceeds gravitational force by a factor of 2 to 1. Since 1,000 V/m is not uncommon in fog, these drops would migrate upward in the earth's normal fog field.

In field measurements using a field mill, fields of 4,000 V/m were consistently generated at ground level by the spraying of charged drops. A 1×10^{-6} meter radius drop charged to 500 electrons would in this field have an electrical force to gravitational force ratio of 8 to 1. A drop with a 8×10^{-6} meter radius has a mass of 512 times, a surface area of 64 times, and a mass/surface area of 8 times that of a drop with a radius of 1×10^{-6} meter. With a constant charge/surface area and a weight proportional to mass, an increase of mass/surface area of 8 to 1 implies an increase of gravitational force to electrical force ratio of 8 to 1, which means that a drop with a radius of 8×10^{-6} meter would be in balance between gravitational and electrical forces, based on calculations for a drop with a radius of 1×10^{-6} meter. It would be reasonable to hypothesize that drops of less than 8×10^{-6} meter radius, with their upward migration resulting from their charge and the local spray-generated electric field, could be the vehicles that transport the feedback current causing ground effect, except for the lack of visual evidence. It is noted that reversing drop polarity will not help, as this also reverses the field produced, and these spray-generated local fields overshadow the earth's natural fields; hence, for all practical purposes the electric fields are those produced by the spraying of charged drops.

Appendix B

PRACTICAL APPLICATION OF CHARGING SYSTEMS

Let us consider the effects that might be obtained with a charge close to the Rayleigh limit: 3×10^7 electrons per 50×10^{-6} meter radius drop. In this case the drop would have a collection efficiency of 28. For calculation purposes the following values are assumed.

Radius of drop: 50×10^{-6} meter

Volume of drop: 5.2×10^{-13} m^3

Cross sectional area of drop: 7.9×10^{-9} m^2

Charge per drop: 3×10^7 electrons (4.8×10^{-12} coulomb (C))

Airport area: 2×10^5 m^2

From 4.8×10^{-12} C/drop and 5.2×10^{-13} m^3/drop we obtain a charge per unit volume of 9.2 C/m^3. With a collection efficiency of 28, the effective cross sectional area of a drop with a radius of 50×10^{-6} meter is 2.2×10^{-7} m^2. With the above effective cross sectional area, the number of drops per unit area is 4.5×10^6 drops/m^2; however, statistically about twice this number of drops, or 9.0×10^6 drops/m^2, will be required. With 9.0×10^6 drops/m^2 and 5.2×10^{-13} m^3 of water per drop, we obtain 4.7×10^{-6} m^3 of water per square meter of fog. For an airport with an area of 2×10^5 m^2, 0.94 m^3 of water is required, and at 9.2 C/m^3 a charge of 8.6 coulombs is required for clearing of fog. Assuming an aircraft speed of 150 km/hr and a path parallel to the 2,000-meter length of the airport, a time of 48 seconds is required to cover the airport. To dispense 8.6 coulombs in 48 seconds requires 0.18 ampere.

It is assumed that about 100,000 volts will be required, and that the corona charging system, which might be able to produce the above charge-to-drop-size figures, might be 25% efficient, and therefore about 0.72 ampere would be required. The power requirement of 72 kilowatts is not too formidable. A turbine-generator unit, coupled with the electronics required for the desired emf levels might be practical, although expensive.

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